

RENDLESHAM, SUFFOLK

CHARACTERISING METALWORKING THROUGH A GEOCHEMICAL SURVEY OF PLOUGHSOIL

TECHNOLOGY REPORT

Joanna Dunster, David Dungworth and Andrew Lowerre



This report has been prepared for use on the internet and the images within it have been down-sampled to optimise downloading and printing speeds.

Please note that as a result of this down-sampling the images are not of the highest quality and some of the fine detail may be lost. Any person wishing to obtain a high resolution copy of this report should refer to the ordering information on the following page.

Rendlesham, Suffolk

Characterising metalworking through a geochemical survey of ploughsoil

Joanna Dunster, David Dungworth and Andrew Lowerre

NGR: TM3254

© English Heritage

ISSN 2046-9799 (Print)

ISSN 2046-9802 (Online)

The Research Report Series incorporates reports by the expert teams within the Investigation & Analysis Division of the Heritage Protection Department of English Heritage, alongside contributions from other parts of the organisation. It replaces the former Centre for Archaeology Reports Series, the Archaeological Investigation Report Series, the Architectural Investigation Report Series, and the Research Department Report Series.

Many of the Research Reports are of an interim nature and serve to make available the results of specialist investigations in advance of full publication. They are not usually subject to external refereeing, and their conclusions may sometimes have to be modified in the light of information not available at the time of the investigation. Where no final project report is available, readers must consult the author before citing these reports in any publication. Opinions expressed in Research Reports are those of the author(s) and are not necessarily those of English Heritage.

Requests for further hard copies, after the initial print run, can be made by emailing:

Res.reports@english-heritage.org.uk

or by writing to:

English Heritage, Fort Cumberland, Fort Cumberland Road, Eastney, Portsmouth PO4 9LD

Please note that a charge will be made to cover printing and postage.

SUMMARY

This research investigates the usefulness of portable X-Ray Fluorescence spectroscopy to detect trace elements in the plough soil, which can indicate past anthropogenic activity. The site under study in this research has artefactual evidence for metal-working, and data from geophysical survey, field-walking, metal-detecting and aerial survey are available for comparison. Geochemical data were plotted against Global Positioning System readings to display soil elemental composition spatially. It was hoped to develop a methodology for geochemical techniques to detect sub-surface archaeology with relatively little cost or disruption.

ACKNOWLEDGEMENTS

With thanks to the landowner and staff for access to the land. GPS support was graciously provided by Tom Cromwell. This research would not have been possible without the enthusiastic and generous collaboration of Chris Scull and Judith Plouviez, and the Rendlesham Research Group.

ARCHIVE LOCATION

Fort Cumberland, Portsmouth, PO4 9LD

DATE OF SURVEY

2011

CONTACT DETAILS

Fort Cumberland, Portsmouth, PO4 9LD

David Dungworth; 023 9285 6783; david.dungworth@english-heritage.org.uk

Andrew Lowerre; 023 9285 6765; andrew.lowerre@english-heritage.org.uk

CONTENTS

INTRODUCTION	1
LITERATURE SURVEY	1
Why do people carry out geochemical analysis of soil	1
Types of survey: areas with no excavation	1
Types of survey: areas within excavations	2
Treatment of soil samples	2
Interpretation: soil chemistry	3
Interpretation: geology.....	3
Interpretation: human settlement and cultivation	4
Interpretation: industry	4
THE SITE	5
METHODOLOGY	10
RESULTS.....	12
Testing for spatial clusters and outliers of values.....	14
Interpolation of values from samples	21
Comparing 1m sample grid to 10m sample grid results.....	24
Comparing prediction errors to instrument measurement variation.....	27
Auger cores: geochemical variation with depth.....	27
Comparison between the survey data and crustal abundance	29
DISCUSSION.....	29
CONCLUSION.....	31
REFERENCES.....	31

INTRODUCTION

The identification and characterisation of archaeological sites and landscapes using a range of survey techniques is an essential part of archaeology (Banning 2002; Clark 1990; Haselgrove *et al* 1985; Riley 1987). The importance of such non-destructive approaches is acknowledged in two Activities within the English Heritage National Heritage Protection Plan:

3A4 – Terrestrial Non-Invasive Survey and Ground-Truthing and

4G2 – Ploughzone Archaeology.

In archaeological survey the most commonly used techniques are aerial, geophysical and the collection of surface material (artefacts) from ploughed fields (fieldwalking). An alternative approach comprises the collection of data on soil chemistry (geochemical survey). Geochemical techniques have to date had limited application in archaeology; not least because the chemical analysis of soil samples has usually been time consuming compared to more routinely applied survey techniques.

The use of portable X-ray Fluorescence Spectroscopy (pXRF) is a quick, non-invasive surface technique for obtaining quantified elemental analysis. It can be used in the field and the results obtained in minutes. The current study investigates the usefulness of pXRF for detecting archaeological activity through the geochemistry of plough-soil. The site (Rendlesham) was chosen because it has artefactual evidence which suggested archaeological metal working, which would be expected to leave significant traces of non-ferrous metals in the surrounding soil.

LITERATURE SURVEY

Why do people carry out geochemical analysis of soil

Geochemical analysis has been carried out to measure the elemental composition of soil which can contain traces of past occupation, land-use and industry. It has been used to identify features with no known archaeological traces at the surface level. It has also been used successfully in conjunction with archaeological excavation, to suggest areas for future study at a potential site, or to supplement the information found in an existing site.

Types of survey: areas with no excavation

In areas where there has been no prior excavation, and the subsurface structures are not known, geochemical survey has been used as a method of prospection. A range of target

elements is selected, which might indicate the presence of a settlement or activity, and then the entire area of interest is sampled and tested for anomalous levels of these elements. As this may constitute a large area, the sampling interval is large (> 1 m and frequently 10 m), with regular steps which do not favour any one feature over another.

In one such large, undisturbed field site at Greaulin, Isle of Syke (Entwistle *et al* 1998), the area was divided up according to the existing field system and the number of samples taken in each field was decided according to the field's size. As the ploughsoil was of interest in identifying processes of agriculture, only the top soil was sampled.

Where there is suspected to be a buried site, augers have been used to extract soil without digging a test-pit (Wilson 2009), although Crowther (1997) has advised that care be taken when interpreting sub-surface material, which adds a complicating factor of material loss and gain through deposition, particularly where the age of the site and its formation processes are not known. Bjelajac *et al* (1996), on the other hand, advise a consistent minimum sampling depth of 0.3 m to avoid disturbed plough soil. This applies to known or probable sites where there are no anthropogenic traces at surface level, indicating that the layers of interest are buried.

Types of survey: areas within excavations

On excavated sites, there are usually structures and deposits which can be associated with an archaeological activity or process. The detection of particular elements that may be linked with specific processes/activities may provide support for the interpretation of the function/use of a particular feature, especially when the archaeology is ambiguous. Geochemical survey undertaken during excavation usually employs a small sampling interval (usually < 1 m) in order to detect the limit between a feature and its surround. On the survey of a tell site by Davidson *et al* (2010), the floor levels were sampled using a grid with a 0.5 m interval, and care was taken to ensure that the sampled material was representative of the context. A similar technique was employed in studies of Mayan (Terry *et al* 2004) and Dutch (Oonk *et al* 2009a) houses, where the structures were known and studied, and the focus of the research question was use of space within them. In cases where the research question specifies contexts, these are targeted exclusively, and surrounding areas are sampled as a background level for comparison, as discussed in more detail below. In the study of hearths used at Roman-period *Calleva Atrebatum* (Cook *et al* 2010), all fire-reddened, blackened or charred and surrounding deposits were sampled stratigraphically as they were excavated.

Treatment of soil samples

Most published geochemical surveys have taken soil samples which were then processed and analysed in a laboratory. This has variously included drying and grinding samples followed by ashing or acid digestion to remove the organic fraction. A range of

spectrometric techniques have been employed although most recent studies have employed some variant of Inductively Coupled Plasma Spectroscopy (ICPS). This provides high-quality data: it is accurate and precise and allows the detection of a wide range of elements (in many cases down to ppm).

Interpretation: soil chemistry

Wilson *et al* (2009) found that detection of the elements in soil samples was easy and relatively robust with existing analytical techniques, but interpretation relied on inter-site comparison due to the geological and anthropological variables which can affect the soil composition. Most research questions focus on inorganic elements which are compared with the soil profiles for the local area in order to identify small areas of significantly high or low levels.

Diagnostic elements are categorized by the type of activity or process which caused them to be present in the soil: those found in anthropogenic sites which can be associated with a particular process such as middens and hearths; those which have been linked to settlements but which cannot be attributed to a particular process; and those which vary naturally and are controlled by site geology and formation processes. The most useful examples to date are summarised (Table 1), and discussed in further detail below.

Table 1. Elements and their relevance to geochemical survey (after Wilson et al 2009)

Origin	Elements
Geology/Lithology	Na, Al, Ti, Sc, Zr, Nb, Cd, Cs, Hg
Anthropogenic	P, Ca, Cu, Zn, Sr, Pb
Uncertain	V, Ni, Mn, Rb, Sn, Ba

Interpretation: geology

Entwistle *et al* (1998) suggested three criteria which provide a minimum definition for the usefulness of an element indicating anthropogenic activity. These, in paraphrase, are:

- 1) that the element must have undergone alteration (positively or negatively) through human activity across the site;
- 2) that the effect of this alteration must be readily apparent when compared with normal background variability; and
- 3) that any such alteration must be sufficiently persistent over time to be detectable in the present day.

Middleton and Price (1996) argue that control soils must be taken from layers contemporary with the sampled soils, in order to establish a baseline for the original place

and time, however this relies on identification of a ground level of interest and assumes that this level has not been subsequently disturbed. Entwistle *et al* (1998) also advocate the use of control soils from the immediate surrounding area, but highlight the problem of determining which soils, if any, are unaltered by human processes.

This problem is taken up by Oonk *et al* (2009b) who compare several similar sites of contemporary date in order to illustrate the effect of the different site lithology in each case. Between the categories of “sand”, “clay” and “sandy clay”, there were found to be differences in the intrinsic components of the parent soil, and in its retention of elements from human processes over time. Therefore, control soils should be taken from off-site to establish a local base-line and on-site to establish a site base-line for the natural soil composition.

Interpretation: human settlement and cultivation

One element which has proved reliable in identifying settlements which were inhabited by humans and domestic animals is phosphorous (P), which is concentrated by the consumption of plant and animal matter, and then redeposited in midden contexts, used as fertilizer on arable fields or found in food preparation areas (Craddock *et al* 1985). Terry *et al* (2004) report a false positive P result caused by a rotting tree stump in one area.

Entwistle *et al* (2006), in a later evaluation of their Skye farmstead survey, conclude that the identifying anthropogenic activity is more reliable where there are concentrations of several diagnostic elements in combination, such as K, Sr and Ca (the latter indicating the use of shell sand as an agricultural fertiliser). They found that studying a combination of elements for each activity allowed more precise definition because it would be increasingly less likely that the combination would occur in distinct patches by chance, for instance, P and K as indicative of the deposition of human food waste as opposed to P alone, which could be introduced through animal manure, plant debris or modern fertilizers.

Interpretation: industry

The multi-element approach is more complicated when applied to interpreting industrial processes, which can have assemblages of tools, structures and raw materials that vary between sites, leaving different ranges of elements and concentrations with different survival rates.

Cook *et al* (2010) follow the approach of Terry *et al* (2004), using geochemical survey to answer a specific research question on a known and excavated archaeological site. At Silchester, Hampshire (*Calleva Atrebatum*) readings were taken in a transect over each hearth deposit, and levels of Cu, Zn and Pb were measured for evidence of non-ferrous

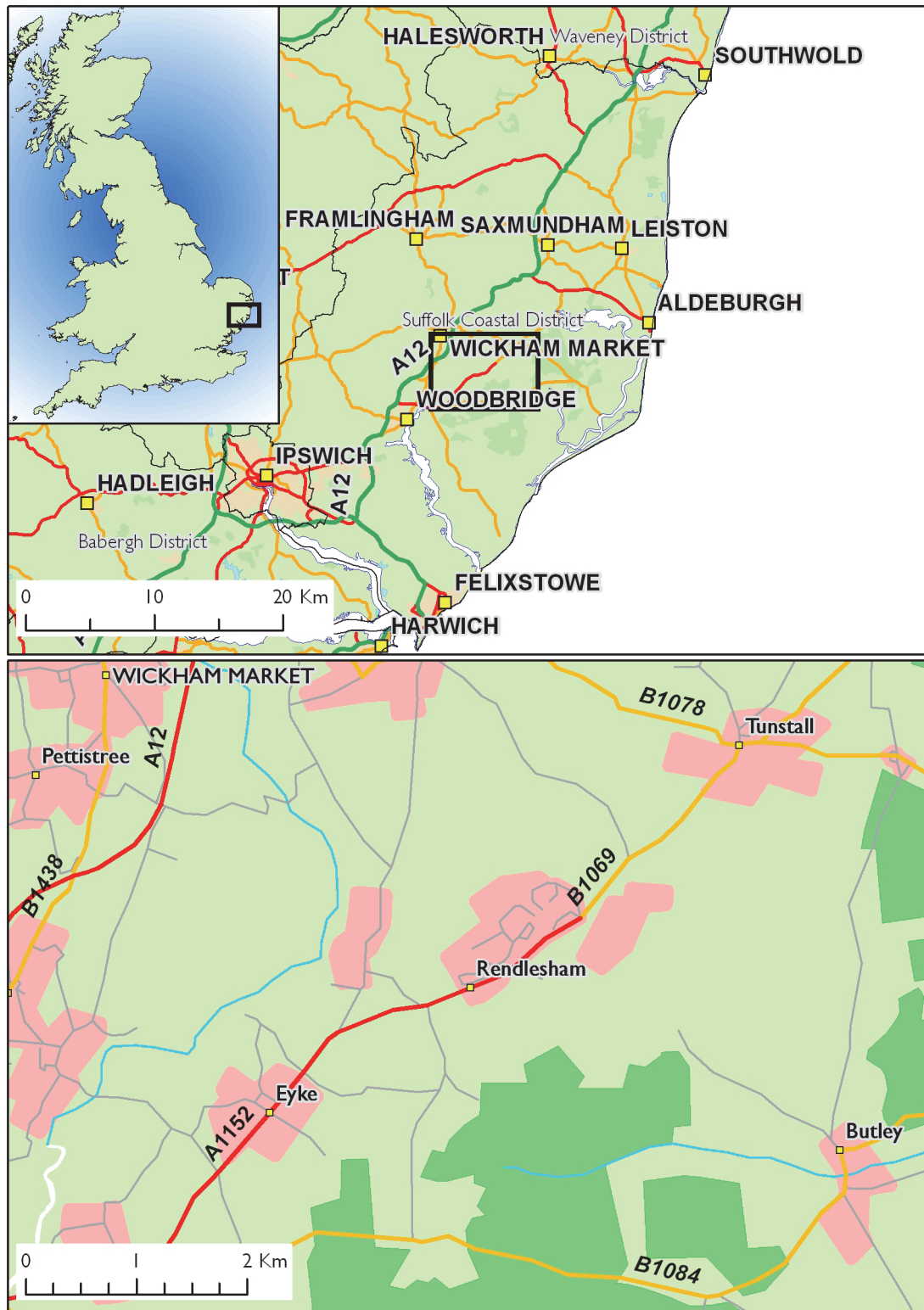
metal working and domestic hearth use. Using a small sampling interval, they were able to resolve areas of interest clearly, and identified 'hot spots' in the areas surrounding hearths where the levels of one or several metals are significantly high. Their results are strongly suggestive, and they attribute this to the strength and persistence of metal working debris as a diagnostic indicator. However, this can also mean that it may drown out nearby domestic hearth signatures and other metal traces, particularly in cases where there is disturbance from later site use or erosion. They also observe that the metals occur in varying combinations and proportions between areas and phases, suggesting that the types of metals being worked and the scale of the working were subject to variation. Alternative explanations for some concentrations were also offered; such as the use of copper cooking vessels at a hearth which showed elevated Cu with background-level Zn and Pb. There is often overlap between the elements present, and interpretation relies on information relating to the site background and any artefacts or structures found.

For this research, the hypothesis is that metal-working processes took place on site, that these left significant enrichment of certain metals, that these traces endured in the ploughsoil to the present day, and that they can be detected using the portable XRF. By plotting the data of enrichment and depletion of these elements, it is hoped to show clearly the areas in which this metal-working took place.

THE SITE

Rendlesham parish is in the south-east of Suffolk (Figure 1), on a spur between two rivers, the Deben and the Alde. In geological terms, it is situated on the boundary between two underlying soil types; namely glacio-fluvial drift and chalky till, with a deep, well-drained soil overlying (Palmer 2009). A tributary of the River Deben runs from north-east to south-west along the western edge of the survey area. There is little alteration in relative relief, and the most common use of land is arable agriculture. The modern region is not densely populated, but it is believed that settlement density has previously been higher, in a network of small settlements with a few larger nuclei (Williamson 2006).

Rendlesham has been described by the 8th-century historian, Bede, as a *vicus regius* (Bruce-Mitford 1974), and has been interpreted as the capital of the *Wuffingas* kings. Anglo-Saxon presence in the area is strongly indicated by the prestigious burials at Sutton Hoo, including the famous ship graves (*ibid*), dated to the immediate pre-Christian period.



Contains Ordnance Survey data © Crown copyright and database right 2012

Figure 1. Location of Rendlesham

The area has been subject to numerous surveys, including aerial photography, field survey (including metal detector survey) and geophysical survey (Loader 2009; Palmer 2009).

The locations of the HER recorded sites and events are given in Figure 2. The East Anglian Kingdom survey used metal-finds in conjunction with ceramics to locate and date settlements. The population was found to have declined during the Late Roman period to a low level in the Early Saxon period. At Rendlesham, evidence was found for continuous occupation from the Early Saxon period onwards (Newman 1992). Limited excavation at RLM 011 ahead of the construction of a new farm structure, in April 1982, revealed five linear ditches, four of which ran parallel, containing ceramic material dated to the Anglo-Saxon and later medieval periods (Plouviez 2009). Bone and oyster shell were found in one pit containing darker soil, while another of the ditches yielded two pieces of copper-alloy sheet, interpreted as decorative binding strips from a vessel such as a bucket. These helped to date the context to the Early Saxon period, and provided a possible link with the wealthy assemblage at Sutton Hoo.

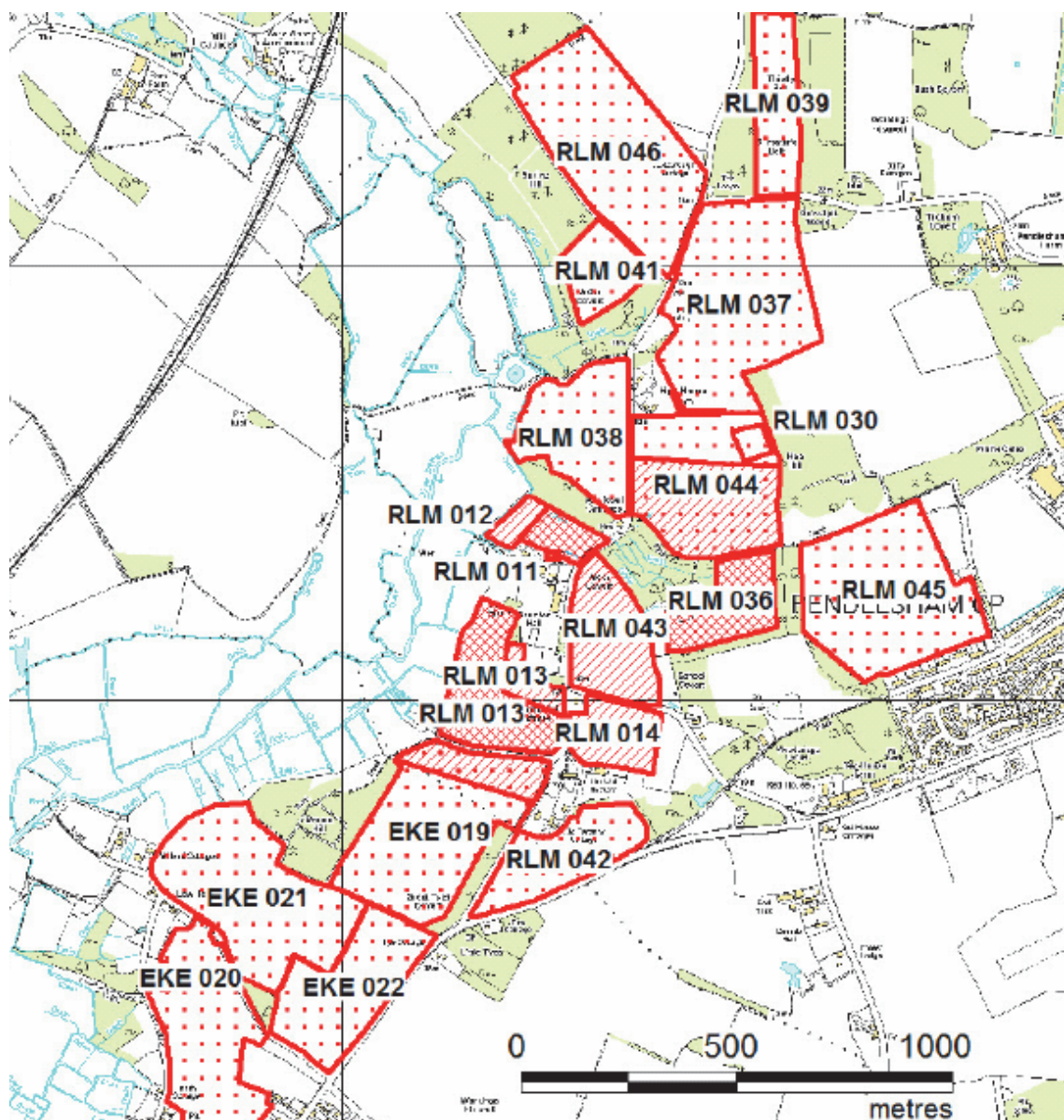


Figure 2. Survey area showing HER sites (Plouviez 2009)

A further period of study from August 2008 included examining aerial photographs of the area. A clear ring-ditched enclosure and a linear feature were visible in RLM 013, and linear features interpreted as former field boundaries in 014. Nothing could be conclusively identified in 036 (Palmer 2009).

Additionally, a geophysical survey using magnetometry was carried out in November 2008, revealing a number of pits and deposits in RLM 013, which also contained larger curvilinear features and ditches associated with a distinct D-shaped ditch enclosure (Woodhouse 2008). This was dated to the Saxon period on the basis of similarity to another locally-excavated example, a farmstead at the site for the Whitehouse Industrial Estate, Ipswich (Martin *et al* 1996), and this conclusion was supported by finds of Saxon ceramic sherds in the plough-soil (Woodhouse 2008).

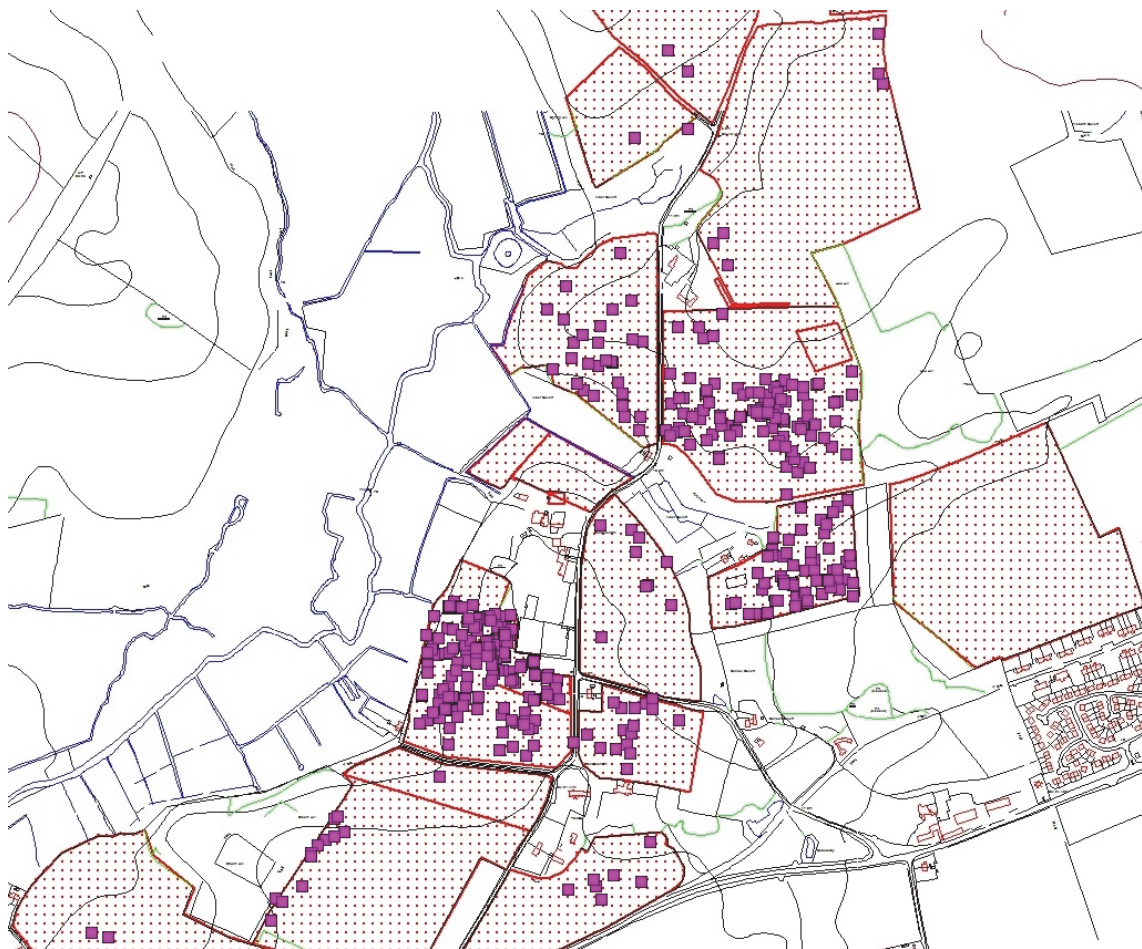


Figure 3. Anglo-Saxon material from surveyed area (Plouviez 2009)

Metal-detecting survey has found evidence for the Romano-British occupation of the site in all areas sampled, with the majority in RLM 013. Anglo-Saxon evidence includes prestigious gold objects and coins mostly concentrated in RLM 013, and copper alloy decorative items, which are also found in other areas surveyed. Medieval coins and fittings were found across the surveyed area, the highest quantities present in the southern part

of RLM 013. Detailed discussion of the findings from all periods and their distribution can be found in the research synthesis by Plouviez (2009; see also Figure 3), and summarised results for selected areas relevant to this study are given in Table 2 below.

For the present study, it is relevant to note the abundance of non-ferrous metal objects and waste returned from the metal-detecting survey of the fields, and in particular RLM 013 (Figure 2). Plouviez (2009) draws a comparison between the volume of finds at this site and those from other contemporary “productive sites” in East Anglia.

Table 2. Summary of the relevant information prior to the geochemical survey

Field Number	RLM 013	RLM 014	RLM 037
Field Name	The Park (or Green Barn Field or Orchard Hill)	Kitchen Piece (or Kitchen Field)	Lyn Croft
Field Walking	Scarce, dispersed ceramic sherds, clusters of animal bone frequently associated with ceramics	Cluster of AS ceramic in south end, brooch found nearby	Cluster of Roman material to north end
Aerial Photography	Ring ditch feature (RLM 007), D-shaped ditch enclosure, zig-zag (WWII?) ditch feature	Linear former field boundary	Area of possible soil difference, a possible quarry and possible ditch
Magnetometer / Topographic Survey	Concentric ring ditch feature (RLM 007), D-shaped ditch enclosure, oval enclosure, various linear features, various small anomalies (Pits? Deposits?)	Not included in survey area	Not included in survey area
Metal Detection	30 Roman coins, 8 Roman brooches, 5 Roman utensils, 15 Anglo-Saxon coins, 42 Anglo-Saxon metalworking waste, globules, fragments, sprues etc. (gold, silver, copper-alloy) 25 later Medieval items	1 Roman coin, 1 Anglo-Saxon brooch (copper-alloy)	1 Roman brooch, 1 medieval coin, 6 medieval personal items
Other / Comments	Incomplete survey due to bird-cover maize belts, most likely site for metal-working activities	Settlement, if present, in south end	

In plans produced using the combined survey results, the distribution of archaeological material varies across the site, with dense clusters in RLM 013 and 014; a thin even spread across RLM 036 and 038; and sparse finds in the peripheral fields surveyed.

Three areas were targeted for survey, using modern field boundaries to determine the limits. For traces of metalworking, RLM 013 was the most logical choice based on finds to date. For settlement remains without significant metalworking evidence, RLM 014 was the best choice as it contains scatters of Early Anglo Saxon ceramic and only a single brooch. RLM 037 was chosen as a local baseline which contains no traces of industry or settlement.

METHODOLOGY

For this study, elements were selected which would have been deposited by non-ferrous metal-working (Table 3). A Niton XL3t pXRF was used and the optimum settings were selected to allow useful limits of detection for key elements (Cu, Zn, Pb and Sn), that is close to the average crustal abundance of these elements, within the shortest analysis time (Table 4). Elements associated with precious metalworking (Ag, Au and Hg) were sought, however, the detection limits for these elements were substantially higher than their average crustal abundance.

Table 3. Selected elements which are associated with non-ferrous metal-working and their average crustal abundance (in ppm) (after Rudnick and Gao 2005; Taylor and McLennan 1985)

Element	Associated with	Abundance
Cu	Copper-working, bronze-working, pewter-working	68
Zn	Copper-alloy working	79
As	Impurity in copper alloys	2.1
Ag	Silver-working	0.05
Sn	Tin-working, copper-alloy working	2.2
Sb	Impurity in copper alloys	0.2
Au	Gold-working	0.003
Hg	Gilding	0.07
Pb	Pewter-working, copper-alloy working	10

The pXRF was used with the AllGeo setting and the results compared for six Certified Reference Soils. The results provided information on the limits of detection, allowed calibration of the raw data and indicated the degree of instrumental precision. This indicated accuracies of 20–50ppm (varying between different elements) and precision which was correlated with measured concentration (Table 4).

Table 4. Accuracy, precision and limits of detection for selected elements (in ppm)

Element	Accuracy (ppm, one standard deviation)	Precision (one standard deviation, relative)	LOD
Cu	20	±10%	50
Zn	20	±10%	50
As	50	±10%	40
Ag	25	±10%	70
Sn	25	±10%	60
Sb	25	±10%	40
Au	50	±10%	20
Hg	50	±10%	30
Pb	50	±10%	20

A Leica GS09 GPS device was used in tandem with the pXRF to plot the position of each reading and inform spatial interpretation of the data. For each field two surveys were carried out; in the first a nominal 10m grid was paced out across most of each field and

the positions recorded using the GPS, in the second a small area (10m by 10m) within each field was surveyed at 1m-intervals. Plotting the nominal 10m-interval survey data showed that pacing yielded actual sample intervals of 11.5m (on average) and rather poor control of each survey line. This was most marked for the survey of RLM013 and RLM014 but was addressed for RLM037 through the pacing out of markers at the end of each survey line for RLM037. It was hoped that the collection of data at different intervals would provide information on the effectiveness of varying sampling interval. It was also appreciated that some of the elements sought might display varying degrees of vertical mobility within soil. To investigate this an auger was used to compare soil chemistry with depth.

The geochemical data output from the pXRF was combined with the eastings, northings and elevation data captured using the GPS instrument in Excel. In Excel, all instances of the text '< LOD' (recording where the value for an element at a given sample point was below the instrument's limit of detection) were replaced with a dummy numeric value - 999.99999. This was done to ensure that all the values in every data column could be imported correctly into the GIS as numeric data, rather than string/text data. The Excel spreadsheets were imported into an Access database as six separate tables, one for each field for both the 10m and 1m sampling intervals. For each table, the data type for the fields 'READING' and 'SAMPLE' was changed from double precision numeric to integer numeric. All other fields were left as double precision numeric.

The Access tables were loaded into an ArcGIS version 10 map document and X-Y 'Event' layers created from each one, using 'EAST' for the X coordinate, 'NORTH' for the Y coordinate, and 'HEIGHT' for the Z (elevation) value. Each 'event' layer was exported to a Point-Z feature class in an Esri ArcGIS version 10 file geodatabase. In the fields recording the surveyed values for each element, records having the dummy value - 999.99999 were selected and the relevant values recalculated to 'Null' (ie, no data, rather than 0 (zero)).

RESULTS

The survey took place over four days and including acquiring geochemical (pXRF) and spatial data (GPS) at 10m intervals from a total of 972 survey points covering a combined area of 11.8ha (Table 5). Data was collected from a further 300 survey points at 1m intervals and samples acquired from 11 auger points. The survey was undertaken over a period of several days in late November. The limited hours of daylight slightly restricted the quantity of data that could be obtained one day. The weather was fine (if cold) throughout the survey. The fields had been harvested but not ploughed and so access to the topsoil was not impeded (Figure 4). Both pXRF and GPS equipment performed well in the field (Figure 4).



Figure 4. Geochemical survey: pXRF data collection (DD, crouched) and GPS (JD, upright)

At the 10m interval, it was possible to survey approximately 4.5ha per day (pXRF and GPS data acquisition). Allowing for downloading and merging of the pXRF and GPS datasets and importing into a computer application capable of providing a visual representation of the geochemical data (this was carried out in the evening) would reduce the effective survey rate to a value closer to 4ha per day. An initial inspection of the data showed that of the potentially useful elements associated with metal working (Table 3), only Zn and Pb were routinely detected. Other elements were detected

infrequently (or not at all) and so could not contribute to a geochemical survey. A wide range of other elements were also detected but in most cases their concentration is likely to be the result of geological processes. For comparative purposes the concentration of two of these elements (K and Fe) has been analysed.

Table 5. The mean concentration and standard deviation of selected elements for each of the three fields surveyed

	RLM013		RLM014		RLM037	
Interval	10m*	1m	10m*	1m	10m*	1m
Extent	4.1ha	0.1ha	2.8ha	0.1ha	4.9ha	0.1ha
Readings	326	100	216	100	430	100
K (wt%)	0.69 ± 0.14	0.72 ± 0.12	0.55 ± 0.18	0.53 ± 0.16	0.68 ± 0.11	0.58 ± 0.13
Fe (wt%)	1.61 ± 0.56	1.32 ± 0.22	1.85 ± 0.52	1.48 ± 0.26	1.68 ± 0.47	1.21 ± 0.34
Zn (ppm)	43 ± 9	44 ± 10	43 ± 9	41 ± 8	40 ± 8	38 ± 10
Pb (ppm)	23 ± 5	21 ± 4	27 ± 10	27 ± 5	23 ± 5	22 ± 5

* nominally 10m, actually 11.5m on average

Comparing the values for the various elements at the scale of each field reveals no significant differences in soil composition between the fields. The possibility remains, however, that differences in soil composition within each field may suggest areas of human activity such as metal working, and so it is necessary to examine the data for each field in turn. Put simply, the goal is to identify spatial patterns in the data which are not likely to be the result of random chance and then, if possible, interpret the geochemical and archaeological meaning of whatever patterns might be identified. As noted in Jackson (2007), geochemical prospection by itself does not seem to be very good at 'finding archaeology.' Patterns in the geochemical data should be compared with and interpreted together with other sources of information about archaeological remains in the area being studied, as suggested by Aston *et al* (1998). In one field, RLM013, it is possible to compare sample geochemical values with results from the magnetometry and metal-detecting surveys.

The simplest approach to seeking spatial patterns in the data is to plot the values recorded for each element from each sample, using either a graduated colour scheme or graduated symbol sizes to portray the range of values. There are, however, a number of drawbacks to this method. Meaningful patterns may be difficult to detect through simple visual inspection of the resulting map. More importantly, varying combinations of colours and/or symbol sizes and the number of colour/size classes used to depict the data may suggest patterns even where none exist. Interpreting simple plots of data values in combination with other data (eg, results from metal detecting or magnetometry survey) can also be challenging.

We have used two alternate approaches to examining the data: using spatial statistics to test for clusters of similar values, and interpolating (or predicting) the values at non-sampled locations on the basis of the known values recorded in the samples. All data manipulation and processing was undertaken using Esri's ArcGIS version 10.

Testing for spatial clusters and outliers of values

Testing for spatial clusters of similar values in the sample data is based on the concept of spatial dependence, often referred to as Tobler's 'first law of geography' (Tobler 1970, 236), that values for a variable at locations close together in space tend to be more similar to each other than those for locations which are distant from each other (Lloyd 2009, 55). In spatial statistics, the concept is referred to as spatial autocorrelation, that is, the degree to which data values correlate with each other depending on their spatial location (Cliff and Ord 1973; Mitchell 2005, 104–5). When similar values tend to be located near each other, that is, there are clusters of values, the data are said to exhibit positive spatial autocorrelation. When dissimilar values tend to be located near each other, that is, the values are dispersed, the data are said to exhibit negative spatial autocorrelation. When there is no discernable trend, the data are considered to be randomly distributed.

The most commonly applied test for spatial autocorrelation across a dataset is Moran's Index, referred to as Moran's I (Cliff and Ord 1973; Hodder and Orton 1976, 178–83; Mitchell 2005, 107, 121–6). Moran's I is a global test: it will indicate whether there is positive or negative spatial autocorrelation, or if the data are randomly distributed, ie, whether the data are clustered, dispersed or spatially random. The test does not indicate where spatial clusters are or whether high or low data values exhibit clustering. Calculating a Z-score permits an assessment of the level of confidence in the Moran's I result, that is, how likely any trend indicated by the test might be the product of random chance.

In ArcGIS, the Moran's I test was run on the elements K, Fe, Pb and Zn from the 10m grid data from fields RLM013 and RLM014 five times each, using distance thresholds of 20, 50, 100, 150 and 200m, employing the 'Inverse Distance' spatial conceptualisation, calculating Euclidean distances and without row standardisation.

Table 6. Moran's I test results

Distance Threshold Field	20m		50m		100m		150m		200m	
	M	p	M	p	M	p	M	p	M	p
RLM013Pb	0.1491	<0.0001	0.0994	<0.0001	0.0714	<0.0001	0.0572	<0.0001	0.0448	<0.0001
Zn	0.2658	<0.0001	0.2046	<0.0001	0.1576	<0.0001	0.1179	<0.0001	0.0944	<0.0001
Fe	0.3783	<0.0001	0.2207	<0.0001	0.1023	<0.0001	0.0790	<0.0001	0.0730	<0.0001
K	0.0641	<0.0001	0.0445	0.0001	0.0381	<0.0001	0.0304	<0.0001	0.0243	<0.0001
RLM014Pb	0.3480	<0.0001	0.1450	<0.0001	0.0610	<0.0001	0.0499	<0.0001	0.0479	<0.0001
Zn	0.0414	0.2596	0.0149	0.2450	0.0114	0.0834	0.0064	0.1166	0.0054	0.1184
Fe	0.2539	<0.0001	0.1558	<0.0001	0.1042	<0.0001	0.0809	<0.0001	0.0690	<0.0001
K	0.0975	0.007	0.0464	0.0010	0.0300	<0.0001	0.0184	0.0005	0.0172	0.0003
RLM037Pb	0.1522	<0.0001	0.0768	<0.0001	0.0403	<0.0001	0.0258	<0.0001	0.0233	<0.0001
Zn	0.3422	<0.0001	0.2920	<0.0001	0.2326	<0.0001	0.1823	<0.0001	0.1519	<0.0001
Fe	0.5044	<0.0001	0.4242	<0.0001	0.3150	<0.0001	0.2455	<0.0001	0.2043	<0.0001
K	0.1316	<0.0001	0.1133	<0.0001	0.0868	<0.0001	0.0680	<0.0001	0.0568	<0.0001

As can be seen in Table 6, the Moran's I values were positive for most elements at most distances, indicating there was a slight trend toward clustering, with Z-scores statistically significant at more than 0.0001 confidence level. It should be noted that the Moran's I values were often not very high. The highest Moran's I values were almost always at a distance threshold of 20m. The only exceptions were for Zn in RLM014, where the Moran's I values showed slight clustering but were not significant at more than a 0.1 confidence level. The Moran's I results suggest that, in most cases, there is some clustering of the elements of interest. It is possible that such clusters might be related to past human activity, and so further investigation of the data was warranted.

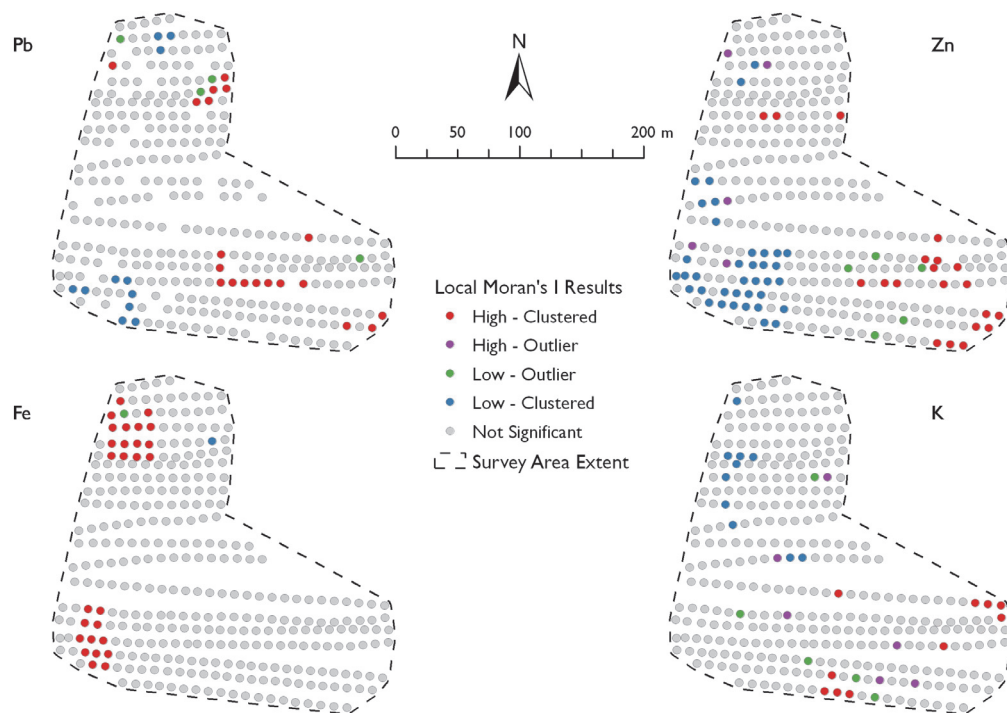


Figure 5. Moran's I_i results for RLM013

As noted above, Moran's I can indicate whether data values exhibit spatial clustering or dispersion, but it does not reveal where any clusters might be. A 'local' version of the test, developed by Anselin (1995; see also Mitchell 2005, 165–74) does enable the location of clusters of similar values. The test – known as Moran's I_i – works by comparing each data value and those of its neighbours with each other and with the average of all values across the whole dataset. When comparing each pair of features, a spatial neighbourhood around each location is defined and weights are applied based either on the adjacency of features or the distance between pairs of features. Moran's I_i seeks to identify significant local clusters of similar values in the data, as well as indicate areas where there are very heterogeneous values. As with the global test, a Z-score is calculated, making it possible to test the statistical significance of each Moran's I_i measurement at a given level of confidence. Doing so enables an assessment of the degree of certainty with which the

value at any location can be said to be part of a group of similar values or to stand out from its neighbours.

In ArcGIS, the Moran's I_i was run on the values for the four elements of interest (K, Fe, Pb and Zn) in the 10m grid datasets from each field. Weighting was based on the inverse Euclidean distance between features with a distance threshold of 20m and no row standardisation. The results have been mapped to depict where there are statistically significant clusters of high or low values as well as statistically significant outliers, ie, low values surrounded by high values and vice versa. The confidence level used was 0.05. Most locations are depicted as 'not significant,' meaning the locations cannot be characterised as either members of clusters of similar values or outliers, surrounded by dissimilar values. Apparent gaps or absent readings are where no value above the limit of detection for an element was recorded in the geochemical survey.

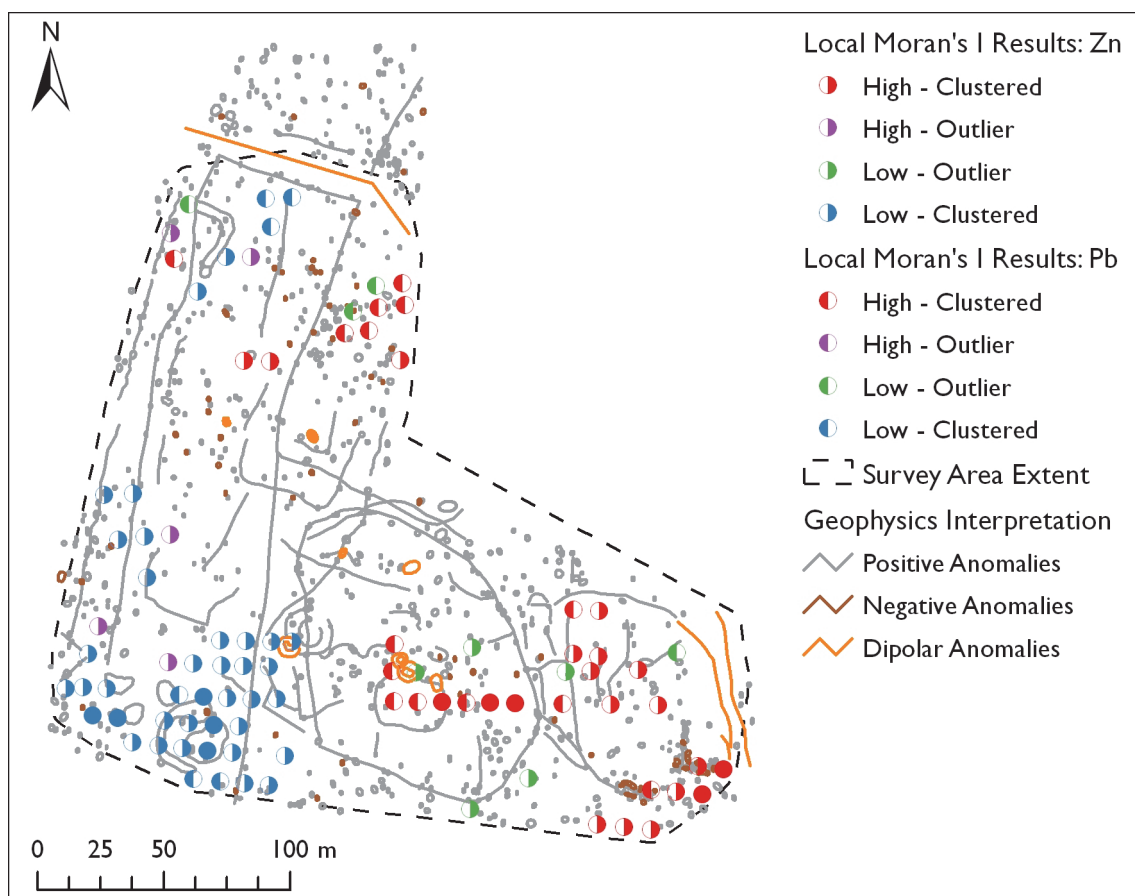


Figure 6. Clusters of Zn and Pb in RLM013 identified by Moran's I_i test overlaid on interpreted magnetometry survey results (from Woodhouse 2008)

Figure 5 shows the results for RLM013. There are clusters of high values for Pb in the eastern portion of the field, as well as to the north of the 'elbow' in the survey area. Small clusters of low Pb values are found in the south-west and north-west corners of the field. There is a similarly broad cluster of high values for Zn in the eastern part of RLM013,

though the distribution is not identical to that for Pb. Low values for Zn cluster in the south-west corner of the field, but the cluster is noticeably larger than that for Pb. In contrast, there are clusters of high Fe values in the north-west and south-west parts of the field. High values for K cluster in the far east and south of the field, with low values in the west.

The clusters of both high and low values for Pb and Zn are generally coincident, but the correspondence is far from exact. If the geochemical values were due to past metalworking activity, it might be expected that the correspondence between the high Pb and Zn values would be closer than it is. The clusters of high Pb and Zn values very roughly coincide with the enclosures revealed by the magnetometry survey, as illustrated in Figure 6, but the correspondence is general at best. The clusters of high Zn and Pb values to the north of the 'elbow' in the survey area do not appear to relate to any obvious group of features revealed by the geophysics. The clusters of low Pb and Zn values in the south-west of the field are in the same general area as features interpreted as natural/geological anomalies in the magnetometry survey (Woodhouse 2008, Fig 11). None of the clusters of either high or low values for Fe or K appear to have any correspondence at all with features revealed in the geophysical survey results.

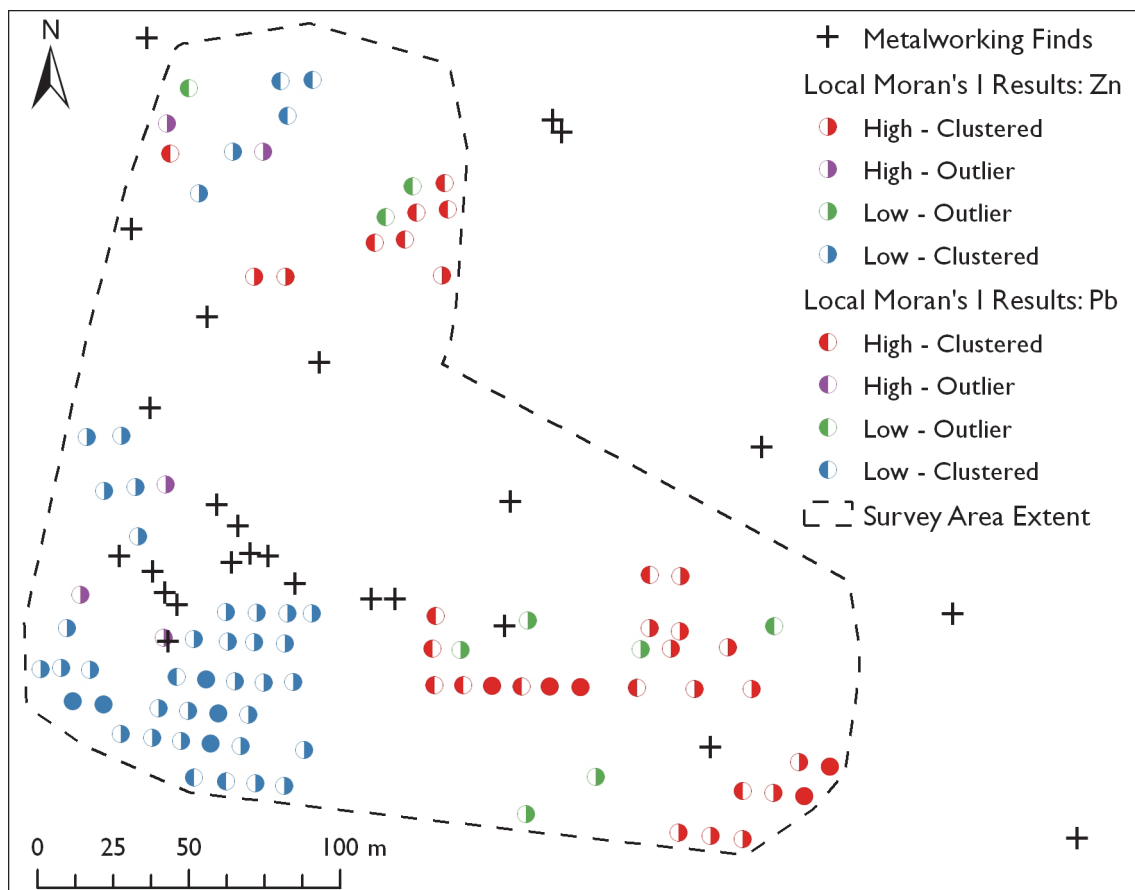


Figure 7. Locations of metalworking finds recovered via metal-detecting survey compared with clusters of Zn and Pb in RLM013 identified by Moran's I_i test

Figure 7 shows that there is also no obvious correlation between the clusters of high Pb and Zn values and the locations of finds relating to metalworking recovered via metal detecting. The locations of metalworking finds and any possible correlation (or lack thereof) between the finds' recorded positions and the geochemical survey results must, however, be treated with the utmost caution. The hand-held GPS equipment used to record the locations of the objects can have positional errors of up to 10m (Plouviez 2009, 8), and no allowance has been made for the distances the objects may have travelled from their original places of deposition due to ploughing. Research on the movement of archaeological objects in ploughsoil suggests that objects can move substantially (often from 5–11m and up to 30m) from their original places of deposition after just a few seasons of ploughing (Clark and Schofield 1991; Boismier 1997; Dickson *et al*/2005; Hopkinson and Timms 2006). Erosion can also lead to considerable movement of objects in ploughsoil (Allen 1991). Analysis of the metal-detected finds explicitly examining their possible movement in the ploughsoil is beyond the scope of the present work. In these circumstances, no conclusions can or should be drawn from the apparent lack of correlation between the geochemical survey results and the metalworking finds recovered via metal detecting.

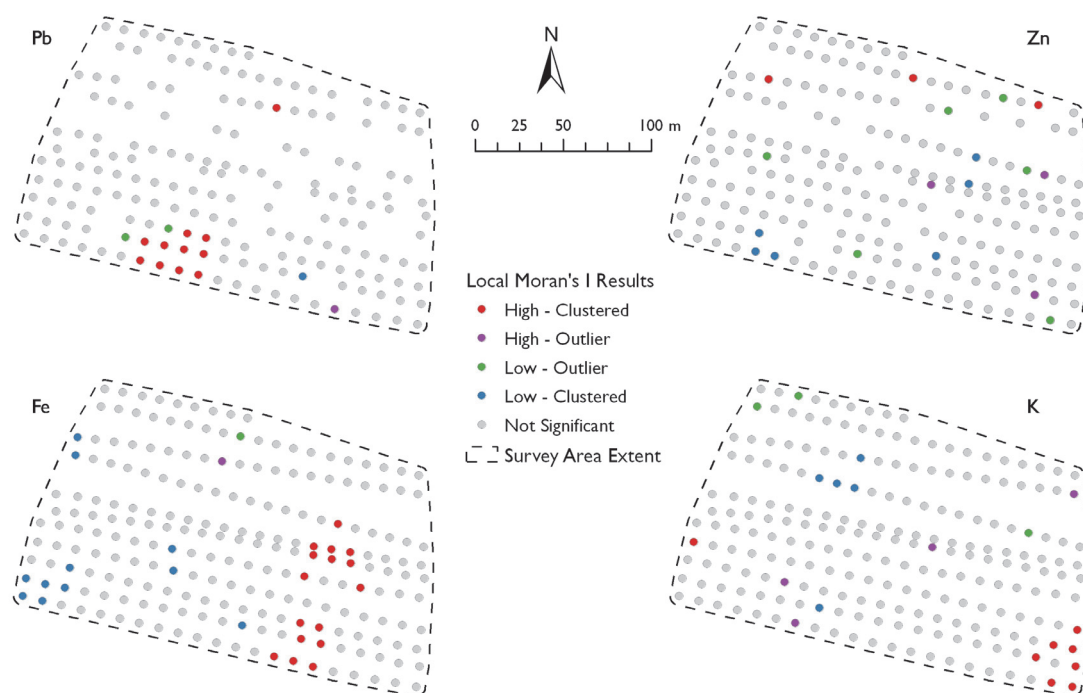


Figure 8. Moran's I_i results for RLM014

Figure 8 illustrates the results of the Moran's I_i test for field RLM014. There is a cluster of high Pb values along the central southern edge of the survey area, but no other distinct clusters of high or low values. As is to be expected given the results of the global Moran's I test, there are no clear clusters of either high or low Zn values. High values for Fe appear in the south-east and central eastern part of the field, with significantly low values

in the south-west. A cluster of high K values is located in the south-east corner of the survey area and low values in the central-northern part.

As shown in Figure 9, the Moran's I_i test applied to the data from RLM037 reveals clusters of high Pb values in the eastern end of the east-west arm of the survey area, in the north-west 'shoulder,' and near the south-east corner of the north-south arm. Low Pb values form a cluster near the joint of the two arms. A large cluster of high Zn values lies in the southern half of the north-south arm, while a similarly large cluster of low Zn values occupies the northern half of the north-south arm. There is a large cluster of high Fe values in the 'shoulder' of the north-south arm of the survey area and small clusters of low values in the centre and southern end of the north-south arm. Slight clusters of high K values appear in the southern end of the north-south arm and in the eastern end of the east-west arm of the survey area. Clusters of low K values lie in the centre of the north-south arm and near the joint of the two arms of the survey area.

In the absence of geophysical and/or metal detecting survey data for RLM104 or RLM037, it is impossible to say whether any of the clusters of values for any of the elements of interest might have any archaeological significance. The lack of any clear correlations in RLM013 between the results of the Moran's I_i analysis of the geochemical survey data on the one hand and the geophysical and metal detecting survey results on the other suggests that clusters indicated in RLM014 and RLM037 are unlikely to be archaeologically meaningful. This suggestion must, however, remain purely speculative until further investigation is undertaken in RLM014 and RLM037.

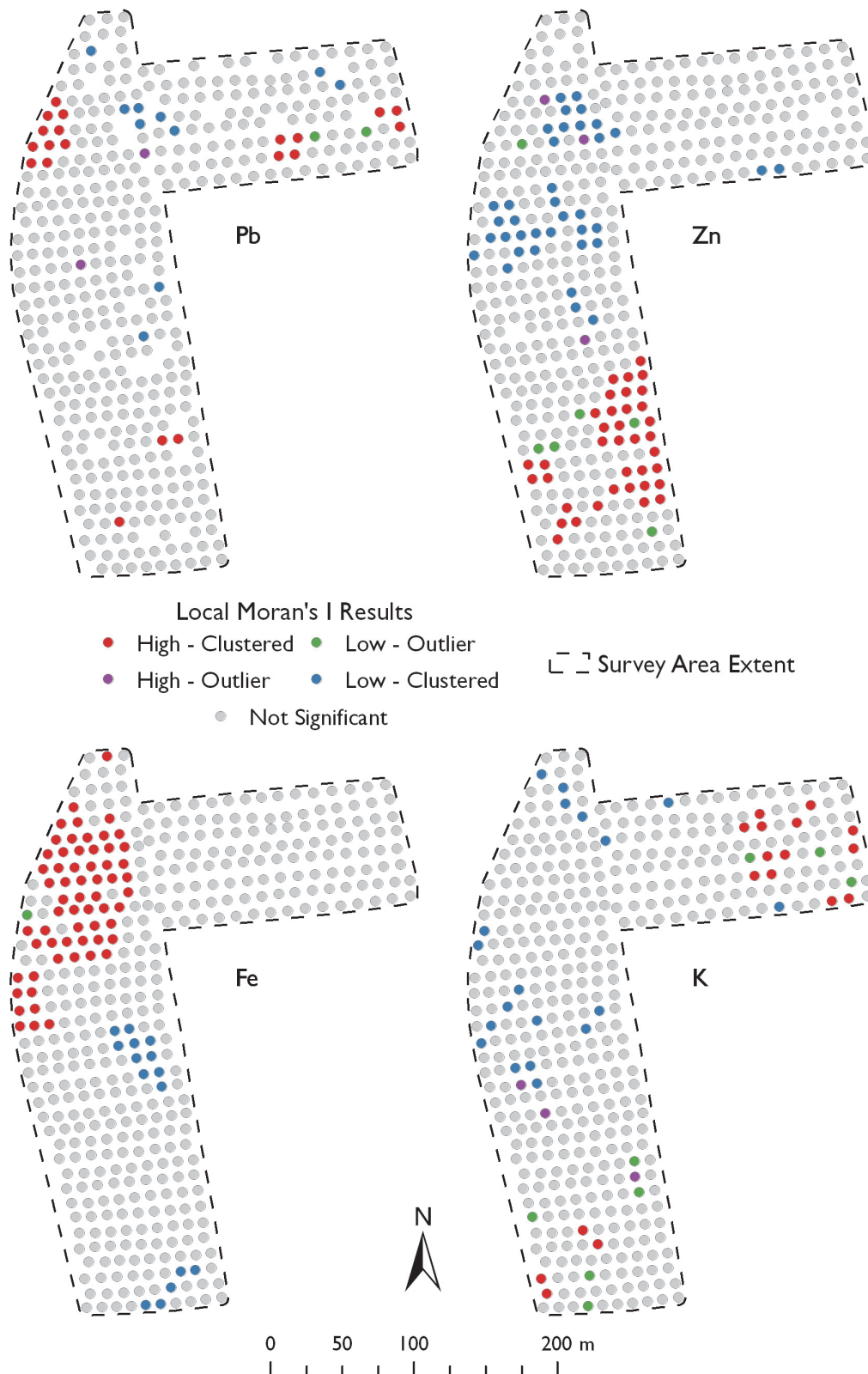


Figure 9. Moran's I_i results for RLM037

Interpolation of values from samples

Discussion and analysis of the survey data so far has treated the sample locations as individual, discrete points in the landscape. The subject of the survey — geochemical variation in the ploughsoil of the three fields — is, of course, a continuous phenomenon. Estimating or interpolating the values for non-sampled locations from known samples allows the creation of continuous surfaces for visualisation and analysis, and a wide range of different interpolation methods is available (Lloyd 2009, 129–54). Robinson and Zubrow (2000) discuss a number of techniques, their potential application to archaeological data and the need to compare and contrast the results of multiple approaches.

An ideal interpolation method balances the desire for the interpolated surface to stay as close as possible to the original data values (ie, to be as exact as possible) and the more subjective desire for a surface that looks smooth to the observer's eye while simultaneously not smoothing away too much detail. The results of any interpolation method can be strongly affected by extreme data values at any sample location. Standard statistical and exploratory data analysis approaches frequently advocate the identification and removal of such outliers, but in this case, extreme sample values for any given element are of interest, assuming they cannot be attributed to measurement error.

We applied four different interpolation methods to the survey data from RLM013: Inverse Distance Weighted (IDW), Local Polynomial Interpolation (LPI), Kernel Smoothing (without barriers) (KS), and Ordinary Kriging (OK). Because of the complexity of creating surfaces using OK and the lack of other archaeological data with which to compare the results, we did not use the technique on the data from RLM014 and RLM037. The Geostatistical Analyst extension in ArcGIS 10 was used to create all the interpolated surfaces.

This is not the place for a detailed description of how each interpolation method works. Lloyd (2009, 134–6) provides further information on IDW. Esri's online Help system describes the background to and functioning of LPI and KS in ArcGIS's Geostatistical Analyst (Esri 2011a; Esri 2011b). Ebert (2002) and Lloyd and Atkinson (2004) discuss the use of geostatistical approaches — including OK — to investigating archaeological data, and Entwistle *et al* (2007) apply OK to geochemical/geoarchaeological data.

For the IDW, LPI and KS methods, the same method-specific parameters were used to produce interpolated surfaces for each of the elements in each of the three fields. For IDW, the weight applied was the simple inverse distance, a standard (non-smoothed) search neighbourhood with a simple (one-sector) circular search radius of 50m was used, and the interpolation algorithm used at least 10 neighbours (sample points) and not more than 25. For LPI, a 3rd order polynomial and exponential kernel function were used, and, as with IDW, a standard (non-smoothed) search neighbourhood with a simple (one-sector) circular search radius of 50m, and the interpolation algorithm used at least 10 and

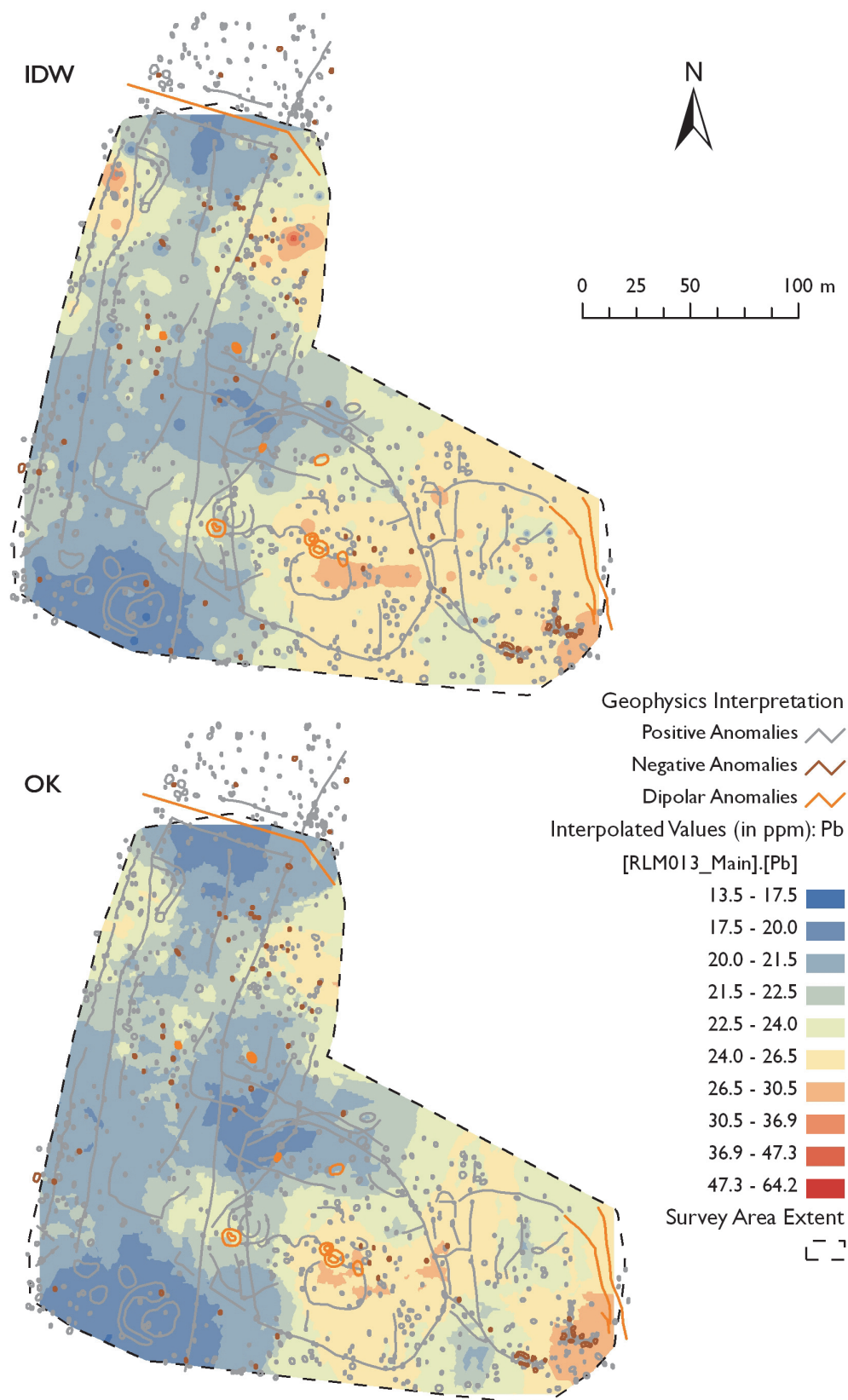


Figure 10. Interpreted magnetometry survey results overlaid on IDW and OK interpolated surfaces for Pb in RLM013

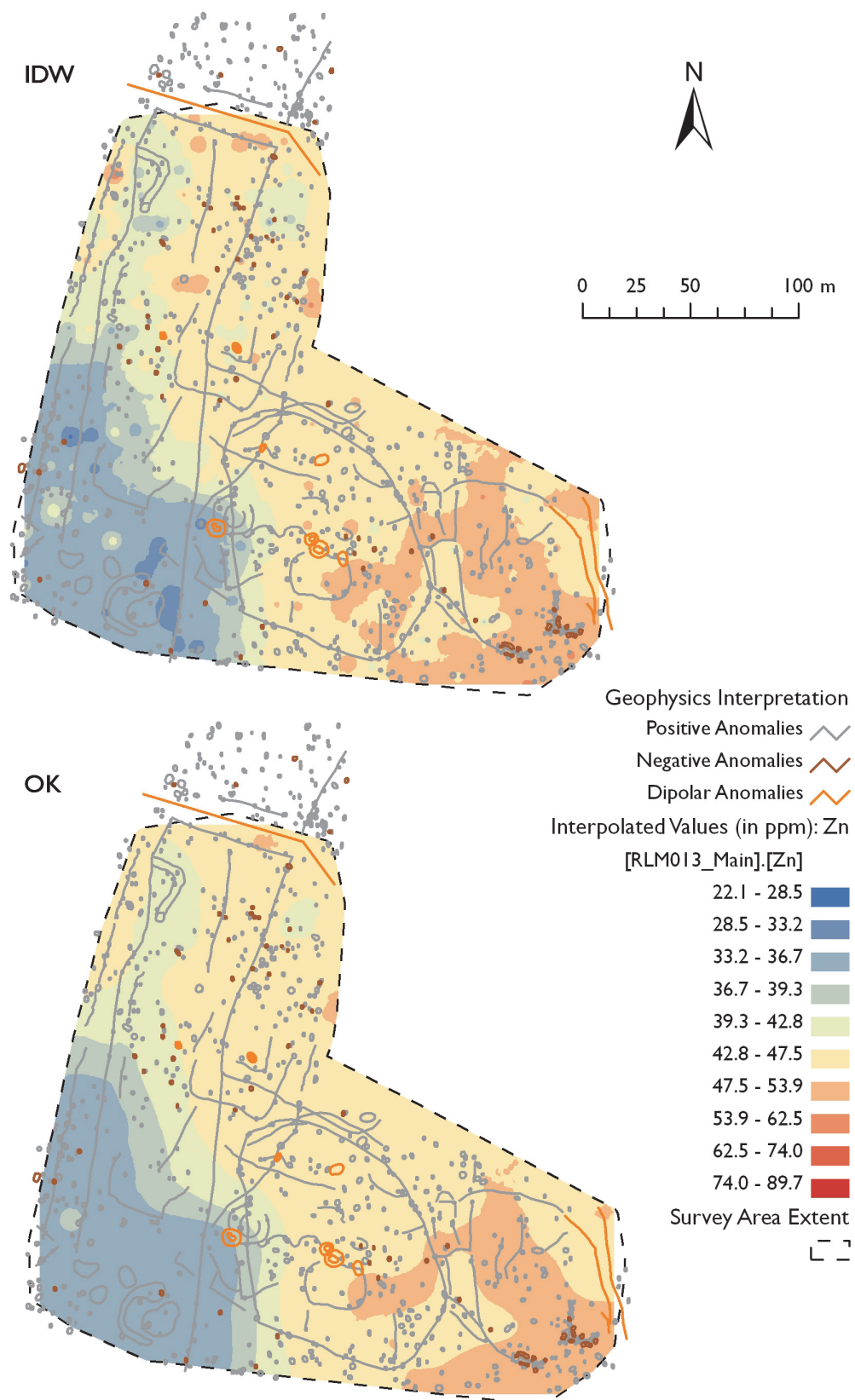


Figure 11. Interpreted magnetometry survey results overlaid on IDW and OK interpolated surfaces for Zn in RLM013

not more than 25 neighbours (sample points). For KS, a Gaussian kernel function and 1st order polynomial were used, with a ridge value of 75 and bandwidth of 50. The search neighbourhood was circular with radius of 50m, using a smoothing factor of 0.2. The models and parameters used to interpolate surfaces using OK for the different elements in field RLM013 are shown in Table 7.

Table 7. Semivariogram models and model parameters used for OK interpolated surfaces

Element	# of Lags	Lag size	Nugget	Model	Partial Sill	Range (m)
K	12	12	583922.69	Rational Quadratic	1272766.251	15.52
Fe	12	6.546	17578731.85	Hole Effect	13652427.853	52.37
Pb*	12	12	0.001450	Gaussian	0.0002234	107.59
Zn	10	11.5	54.441426	Circular	24.637589	92.65

* Data values transformed using Box-Cox (power) transformation with a power of -0.5

By and large, KS produced surfaces that were heavily smoothed, potentially obscuring subtle variations in the data. LPI tended to emphasise the upper and lower ends of the value ranges, producing a somewhat ‘stepped’ effect when mapped. OK and IDW both generally produced results that are visually pleasing without appearing to smooth away too much of the variability in the data. No single method can be preferred to all the others.

Overlaying the interpreted magnetometry results from RLM013 on the interpolated surfaces for Pb and Zn created using IDW and OK (illustrated in Figures 10 and 11) shows no obvious correspondence between features revealed by the geophysical survey and variations in the geochemical data.

Comparing 1m sample grid to 10m sample grid results

As noted in the survey methods section, 10x10m areas within each field were surveyed using a 1m sampling interval, in addition to the 10m sampling interval used for each field as a whole. Collecting the geochemical data at a higher spatial resolution for smaller areas within each field allows us to begin to investigate the question of whether the 10m sampling interval is sufficient to capture meaningful variation in the soil chemistry, or whether a smaller sampling interval might be necessary. This is an important issue for developing the survey methodology deployed here. The higher the spatial resolution of the survey (the smaller the sampling interval) the more time must be taken to collect the data. The lack of any clearly archaeologically meaningful anomalies in the data collected on the 10m-grid limits the extent to which we can explore this question. Nevertheless, it is possible to compare the data collected at the different spatial resolutions and provide some preliminary indications of whether meaningful information has been lost by using the larger sampling interval.

It is possible to compare the mean values for each of the four elements of interest in the 1m grid datasets with mean values for points in the 10m grid datasets which are close to

the areas where the 1m grid datasets were collected. Because the 1m grids were set out 'by eye' in the field, without specific reference to the locations of the 10m-grid sample locations, the location and orientation of the 1m grid datasets are not neatly aligned relative to the 10m-grid datasets. Tables 8–10 show the overall mean for the 1m-grid datasets together with the mean values for the nearest 4–7 and nearest 16–17 points in the 10m-grid datasets for RLM013, RLM014 and RLM037, respectively.

Table 8. Comparison of means for 1m sample grid and nearest 10m sample grid data in RLM013 (all values in ppm)

Element	1m grid mean	10m grid mean nearest 4 points	10m grid mean nearest 16 points
K	7274	7761	7303
Fe	13247	14645	14241
Pb	21.1	23.1	21.3
Zn	43.9	46.0	44.4

Table 9. Comparison of means for 1m sample grid and nearest 10m sample grid data in RLM014 (all values in ppm)

Element	1m grid mean	10m grid mean nearest 7 points	10m grid mean nearest 17 points
K	5274	5412	5738
Fe	14818	14632	15646
Pb	26.7	26.5	26.2
Zn	41.4	38.1	43.6

Table 10 Comparison of means for 1m sample grid and nearest 10m sample grid data in RLM037 (all values in ppm)

Element	1m grid mean	10m grid mean nearest 7 points	10m grid mean nearest 16 points
K	5817	7403	7154
Fe	12135	15312	15662
Pb	21.6	23.2	24.64
Zn	38.2	46.4	46.2

In RLM013 and RLM014, the mean values for the different elements in 1m grid data are generally fairly close to the means for the nearest points in the 10m grid data. In both fields, the 10m grid data appear to over-predict for Fe, ie, the mean values from the nearest points in the 10m grid data are noticeably higher than those for the 1m-grid data. It is worth noting that the values for the two key anthropogenic elements Pb and Zn in RLM013 and RLM014 are quite close in the data from the two different sampling intervals. In RLM037, the mean 10m grid data show marked over-prediction for all four elements compared to the 1m grid data.

Table 11. Mean and root mean squared prediction errors calculated from 1m and 10m sample grids in RLM013 for each element and each interpolation method

Element	Interpolation Method	Mean Error	Root Mean Squared Error
K	IDW	-155	1308
	LPI	337	1358
	KS	-336	1305
	OK	319	1395
Fe	IDW	2517	3519
	LPI	-259	2267
	KS	3337	4038
	OK	641	2761
Pb	IDW	1.5	3.8
	LPI	0.2	3.4
	KS	1.3	3.7
	OK	0.5	3.4
Zn	IDW	0.6	10.4
	LPI	-0.4	10.4
	KS	0.4	10.0
	OK	0.4	10.1

Comparison of the values in the interpolated surfaces derived from the 10m grid data at the locations of the 1m grid samples with the values actually measured provides another indication of how well the 10m resolution data predicts the values in between the sample locations. Using only the data from RLM013, prediction errors between the 10m and 1m grid for each method were calculated. For each sample location in the 1m grid data, the actual (measured) value for each of the four elements was subtracted from the value predicted from the 10m grid data.

The mean and root mean squared prediction errors for each interpolation method for each element are presented in Table 11. The mean error indicates whether a given interpolation method used on the 10m grid data is biased when compared to the 1m grid data, ie, whether it over- or under-predicts values. A positive mean error value shows a tendency toward over-prediction; a negative value a tendency toward under-prediction. The root mean squared error (RMSE) provides a summary of the magnitude of error. An interpolation method producing a large RMSE value is less accurate overall than a method producing a small RMSE value (Lloyd 2009, 153–4).

For Pb and Fe, the least biased method (ie, the one with the mean error closest to 0) was LPI. For K, IDW was the least biased method, and for Zn, KS produced the least biased results. KS was the most accurate (ie, had the lowest RMSE) for Zn and K, while LPI was most accurate for Fe. LPI and OK were equally accurate predictors for Pb. It is worth noting that the RMSE values for all methods for Zn were very similar, as were the values for KS and IDW for K. Examining the mean error and RMSE values together suggests that LPI was the most effective interpolation method for Pb and Fe, IDW was the most effective method for K, and KS and OK were equally effective methods for Zn.

Robust evaluation of whether a 1 m sampling grid is 'better' than a 10 m sampling grid would have required fully surveying at least one of the fields using the higher resolution grid. Sampling the whole of one field at 1 m resolution would have enabled artificially coarsening the resolution down to a 10 m interval, and then investigating the differences between the data at the two different resolutions.

Comparing prediction errors to instrument measurement variation

It is also possible to compare the standard deviation of the prediction error for each element with the standard deviation for the range of values recorded from repeated readings of the same soil sample. If the range of measurement variation exhibited by the pXRF instrument is greater than the range of prediction error, then it is unlikely that any meaningful information has been lost by not taking samples on a 1 m grid for the whole field.

Table 12. Comparison of Std Dev from soil samples and Std Dev for prediction errors between surfaces interpolated from 10 m grid survey data and 1 m grid survey data in RLM013

Element	Std Dev from repeated lab readings of soil samples	Std Dev of prediction error for			
		IDW	LPI	KS	OK
K	411	1305	1322	1268	1365
Fe	2655	2471	2264	2285	2699
Pb	3.0	3.8	3.7	3.7	3.7
Zn	5.5	10.5	10.5	10.1	10.2

All four interpolation methods have a noticeably higher range of variation in their prediction error for K and Zn than the range of measurement variation in the pXRF instrument. This suggests that the coarser survey resolution could be missing — and effectively masking — more variation in the element values than can be attributed to measurement inaccuracy. In contrast, the range of variation in the prediction error for Fe and Pb is quite close to the measurement variation in the instrument, suggesting that little information has been lost. The equivocal nature of these results mean that no conclusive statement can be made regarding comparison of the prediction errors and measurement error in the pXRF itself.

Auger cores: geochemical variation with depth

It has been reported that some geochemically important elements can be mobile within soil horizons (eg Maskell *et al* 1996; Whitehead *et al* 1997). The possibility that such a mechanism had led to a depletion of important elements at the surface of the ploughsoil was investigated through a small auger survey. A screw auger was used to extract soil samples from depths of up to 0.6 m from four separate points within RLM013 (Figure 12). The soil/sediment was divided into vertical sections (0.05–0.10 m) using, where possible,

variations in the colour and texture of soil as a guide to the divisions between the sections.

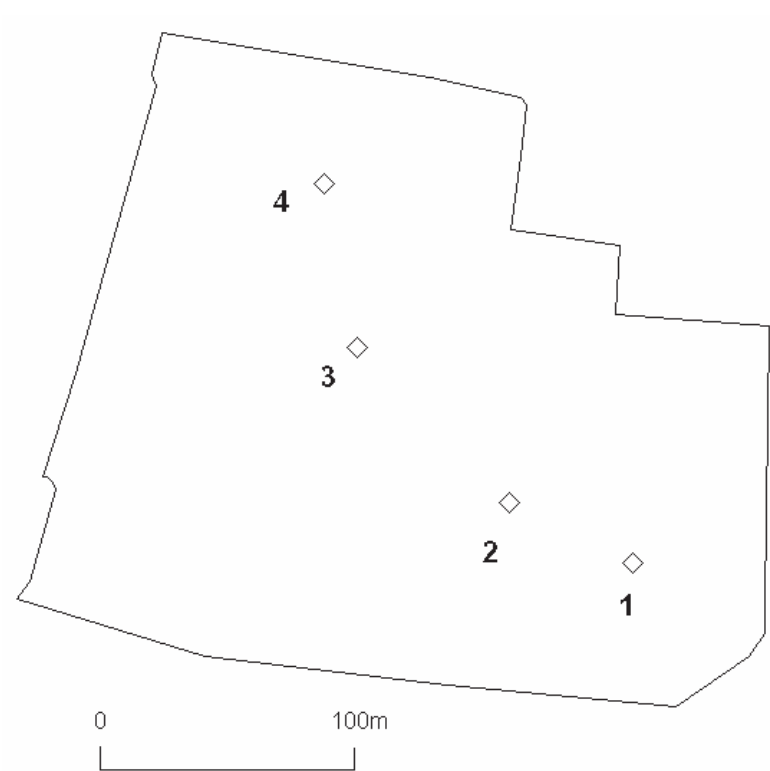


Figure 12. RLM013 showing the locations of the four auger sampling pints

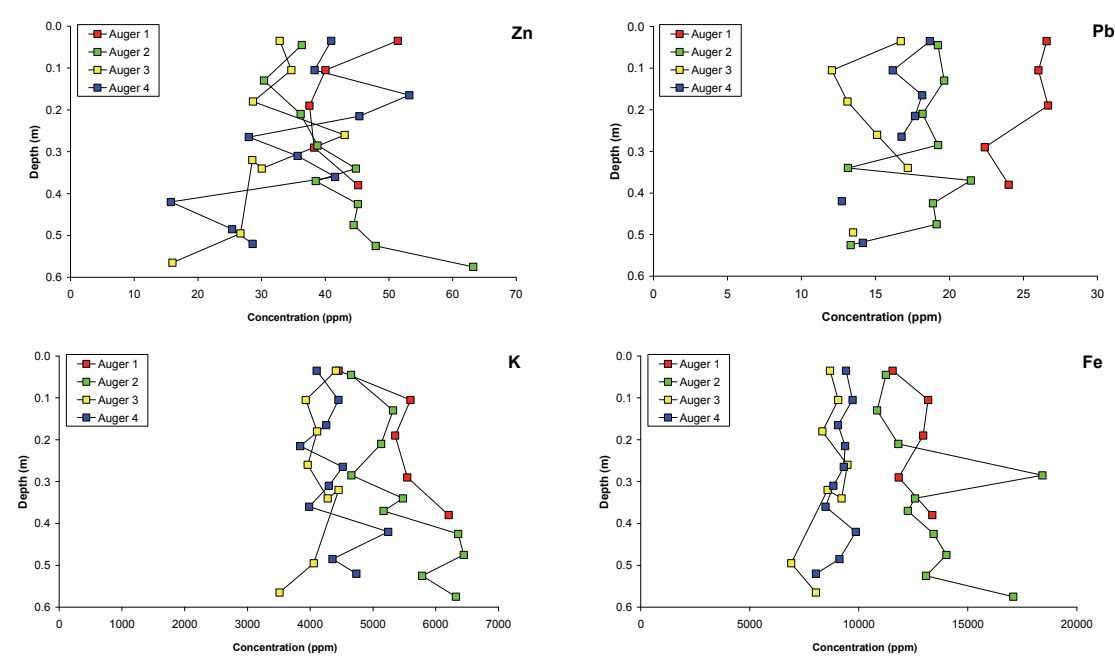


Figure12. Changes in soil chemistry (Zn, Pb, K and Fe) with depth (m) from four auger points in RLM013 (see figure 11)

The auger soil samples were analysed using the pXRF in a similar manner to the survey data reported above. The concentration of various elements were compared with the depth of soil (Figure 13). The concentration varies with depth but the variations are generally rather small (Table 13) and show no clear or consistent changes with depth.

Table 13. Comparison of mean and standard deviations for selected elements from the auger survey (RLM013)

	Auger 1	Auger 2	Auger 3	Auger 4	1m-grid	10m-grid
Zn	42.5±5.8	42.6±9.0	30.1±7.7	35.3±11.0	43.9±10.1	43.0±9.3
Pb	25.1±1.9	18.0±2.9	14.6±2.1	16.3±2.2	21.1±3.7	22.9±5.1
K	5432±635	5532±674	4089±305	4378±400	7274±1276	6962±1375
Fe	12576±828	13478±2470	8533±810	9118±556	13248±2235	16145±5590

Comparison between the survey data and crustal abundance

The detailed analysis of the geochemical survey data and the auger data shows very low levels of variation spatially or with depth. For the most part this variation is comparable with the analytical precision of the equipment used. The overall concentrations of the two elements detected and expected to have potential to indicate past metalworking (Zn and Pb) are given in Table 14. This data shows the average values and standard deviations for each field as well as the average crustal abundance (Rudnick and Gao 2005; Taylor and McLennan 1985). The zinc concentrations from the Rendlesham survey are in almost all cases slightly lower than the crustal average while the lead concentrations are slightly higher. When compared against a regional dataset (Scheib 2007), however, it is clear that the Rendlesham data displays values which are close to the regional average. The fact that the Rendlesham data for Zn and Pb are close to the regional averages suggests that these two elements are not enhanced at Rendlesham.

Table 14. Mean and standard deviations for selected elements (ppm) for the three field surveyed compared with BGS data for East Anglian topsoil (Schreib 2007) and average crustal abundance (Rudnick and Gao 2005; Taylor and McLennan 1985)

Element	RLM013	RLM014	RLM037	Schreib	Average Crustal Abundance
Zn	43.0±9.3	43.2±9.3	39.9±8.4	59.5±18.8	80
Pb	22.9±5.1	27.2±10.1	22.5±5.4	28.8±21.5	10

DISCUSSION

On a purely practical level, it is clear that the survey and data processing methodologies developed for this survey have worked well. The data collected using the pXRF combined with spatial coordinates captured using differential GPS can be readily converted into data usable in GIS software. Once in a GIS environment, the data can be analysed using a

variety of spatial statistical and interpolation methods. The analysis of the data capture records suggests that (using a 10m grid) up to 4ha can be surveyed per day which comparable well with some conventional geophysical survey techniques.

Global tests for spatial autocorrelation indicated clustering of values for the four elements of interest in all three fields, and local tests highlighted the locations of significant clusters of both high and low values for those elements. Comparison of the clusters in RLM013 for the elements Pb and Zn with data from magnetometry and metal-detecting survey did not reveal any clear correspondence between the geochemical survey results and those of the other survey methods. In general, the overall low concentrations of the elements of interest mean that the results of the analytical tests may be statistically significant, but they are not archaeologically significant.

Interpolation of surfaces based on the sample points allowed further visualisation of the geochemical survey results. Using multiple interpolation methods for each element in each field allowed us to compare the effectiveness of the different methods. No one interpolation method was clearly preferable to the others. As was the case with the cluster analysis, the interpolated surfaces created for the elements Pb and Zn showed no meaningful correspondence with the geophysical survey results.

Comparison of the data collected at 1m resolution with those collected at 10m resolution also enabled investigation of the relative effectiveness of the two sampling intervals. In general, the 10m resolution data appear to overestimate values for the elements of interest when compared to those collected at 1m resolution. The degree of overestimation varied between the four elements. The different interpolation methods used on the 10m resolution varied from element to element in the degree to which they over- or under-predicted values. It is not clear whether significant information might have been missed using the coarser sampling interval. Further work, in particular a complete survey at 1m or 5m resolution, is required to assess whether the 10m sampling interval is sufficient to capture data detailed enough to allow meaningful interpretation.

The limited variation in the geochemical data and the difficulty of relating possible spatial anomalies to data from other survey techniques suggests that the variation is not archaeologically significant. This impression is reinforced by the observation that the average values for Pb and Zn are close to the expected background levels of these two elements in East Anglian soils. The auger data suggests that the low levels of Pb and Zn at the surface reflect the concentrations of these elements in the soil as a whole and that these elements have not been leached away from the topsoil. It is likely, therefore, that any past metalworking activity at Rendlesham was temporary/episodic rather than intensive.

CONCLUSION

The development of electrically-cooled x-ray detectors and the miniature x-ray generating tubes has in the past few decades allowed the production of portable XRF instruments. These are increasingly used to analyse materials outside the laboratory, in particular for near real-time surveys for mining exploration and assessment of land contamination (eg Higuera *et al* 2012). The success of such geochemical applications suggests that there is potential for their application in archaeology. Geochemical surveys have been used for many decades in archaeology but these have largely used laboratory-based techniques to analyse soil collected in the field. In order to exploit the unique attributes of pXRF, we have undertaken analysis of soil *in situ* in the field using the lowest count time that would still allow the detection of 20–100ppm of various elements that should be enhanced by non-ferrous metal melting and casting. We have demonstrated that the technique works but, for the area surveyed for this report, were unable to detect any enhancement of key elements or any convincing spatial anomalies that could be correlated with other archaeological survey evidence.

REFERENCES

- Allen, M J 1991 'Analysing the landscape: a geographical approach to archaeological problems', in Schofield, A J (ed) *Interpreting Artefact Scatters: contributions to ploughzone archaeology*. Oxford: Oxbow Books, 39–57
- Anselin, L 1995 'Local indicators of spatial association—LISA'. *Geographical Analysis* 27(2), 93–115
- Aston, M A, Martin, M H and Jackson, A W 1998 'The potential for heavy metal soil analysis on low status archaeological sites at Shapwick, Somerset'. *Antiquity* 72(278), 838–847
- Banning, E B 2002 *Archaeological Survey*. New York: Kluwer Academic Press
- Bjelajac, V, Luby, E M and Ray, R 1996 'A validation test of a field-based phosphate analysis technique'. *Journal of Archaeological Science* 23, 243–248
- Boismier, W A 1997 *Modelling the Effects of Tillage Processes on Artefact Distributions in the Ploughzone: A Simulation Study of Tillage-Induced Pattern Formation*. Oxford: Archaeopress
- Bruce-Mitford, R 1974 *Aspects of Anglo-Saxon Archaeology*. London: Trinity Press
- Clark, A 1990 *Seeing Beneath the Soil*. London: Batsford

Clark, R H and Schofield, A J 1991 'By experiment and calibration: an integrated approach to archaeology of the ploughsoil', in Schofield, A J (ed) *Interpreting Artefact Scatters: contributions to ploughzone archaeology*. Oxford: Oxbow Books, 93–105

Cliff, A D and Ord, J K 1973 *Spatial Autocorrelation*. London: Pion

Cook, S R, Banerjee, R Y, Marshall, L-J, Fulford, M Clarke, A and van Zwieten C 2010 'Concentrations of copper, zinc and lead as indicators of hearth usage at the Roman town of *Calleva Atrebatum* (Silchester, Hampshire, UK)'. *Journal of Archaeological Science* 37, 871–879

Craddock, PT, Gurney, D, Pryor, F and Hughes, MJ 1985 'The application of phosphate analysis to the location and interpretation of archaeological sites'. *Archaeological Journal* 142, 361–376

Crowther, J 1997 'Soil phosphate surveys: critical approaches to sampling, analysis and interpretation'. *Archaeological Prospection* 4, 93–102

Davidson, DA, Wilson, CA, Lemos, I and Theodoropoulos, S P 2010 'Tell formation processes as indicated from geoarchaeological and geochemical investigations at Xeropolis, Euboea, Greece'. *Journal of Archaeological Science* 37, 1564–1571

Dickson, A, Hopkinson, G and Timms, S 2005 *The Effects of Agricultural Practices on Archaeological Remains* [web page]. York: Mike Griffiths & Associates/Archaeological Planning Consultancy. Retrieved 5 March 2012 from http://www.archaeologicalplanningconsultancy.co.uk/mga/pages/report_deliver.php?Unique_ID=3&Page=1/1

Ebert, D 2002 'The potential of geostatistics in the analysis of fieldwalking data', in Wheatley, D, Earl, G and Poppy, S (eds) *Contemporary Themes in Archaeological Computing*. Oxford: Oxbow Books, 82–89

Entwistle, J A, Abrahams, P W and Dodgshon, R A 1998 'Multi-element analysis of soils from Scottish historical sites, interpreting land-use history through the physical and geochemical analysis of soil'. *Journal of Archaeological Science* 25, 53–68

Entwistle, J A, McCaffrey, K J W and Dodgshon, R A 2006 'A pedological approach to reconstructing land-use and settlement form in the Hebrides: lessons for the future', in Jones, R E and Sharpe, L (eds) *Going over Old Ground: perspectives on archaeological geophysical and geochemical survey in Scotland*. Oxford: Archaeopress, 128–142

Entwistle, J A, McCaffrey, K J W and Dodgshon, R A 2007 'Geostatistical and multi-elemental analysis of soils to interpret land-use history in the Hebrides, Scotland'. *Geoarchaeology* 22(4), 391–415

Esri 2011a *ArcGIS Desktop 10 Help: How Kernel Interpolation With Barriers works* [web page]. Last updated 11 February 2011. Retrieved 15 February 2012 from http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/How_Kernel_Interpolation_With_Barriers_works/00310000002w000000/

Esri 2011b *ArcGIS Desktop 10 Help: How local polynomial interpolation works* [web page]. Last updated 11 February 2011. Retrieved 15 February 2012 from http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/How_local_polynomial_interpolation_works/003100000027000000/

Haselgrove, C, Millett, M and Smith, I (eds) 1985 *Archaeology from the Ploughsoil*. Sheffield: Department of Archaeology and Prehistory

Higuerasa, P, Oyarzunb, R, Iraizozc, J M, Lorenzoa, S, Esbría, J M and Martínez-Coronadoa, A 2012 'Low-cost geochemical surveys for environmental studies in developing countries: testing a field portable XRF instrument under quasi-realistic conditions'. *Journal of Geochemical Exploration* 113, 3–12

Hodder, I and Orton, C 1976 *Spatial Analysis in Archaeology*. Cambridge: Cambridge University Press

Hopkinson, G and Timms, S 2006 *Further Monitoring on the Effects of Ploughing on Archaeological Remains* [web page]. York: Mike Griffiths & Associates/Archaeological Planning Consultancy. Retrieved 5 March 2012 from http://www.archaeologicalplanningconsultancy.co.uk/mga/pages/report_deliver.php?Unique_ID=4&Page=1/1

Jackson, A 2007 'Archaeological soil analysis', in Gerrard, C and Aston, M (eds) *The Shapwick Project, Somerset. A Rural Landscape Explored*. London: The Society for Medieval Archaeology, 183–200

Lloyd, C D 2009 *Spatial Data Analysis: An Introduction for GIS Users*. Oxford: Oxford University Press

Lloyd, C D and Atkinson, P M 2004 'Archaeology and geostatistics'. *Journal of Archaeological Science* 31 (2), 151–165

Loader, T A 2009 'Rendlesham Fieldwork 1982', in Plouviez, J (ed) *Archaeological Survey Report: Naunton Hall, Rendlesham RLM 011, 012, 013, 014, 036*. Ipswich: Suffolk County Council

Martin, A, Plouviez, J and Pendleton, C 1996 'Archaeology in Suffolk 1995' *Proceedings of the Suffolk Institute of Archaeology and History* 38, 476–478

- Middleton, W D and Price, T D 1996 'Identification of activity areas by multielement characterization of sediments using inductively coupled plasma-atomic emission spectroscopy'. *Journal of Archaeological Science* 23, 673–687
- Mitchell, A 2005 *The ESRI Guide to GIS Analysis Volume 2: Spatial Measurements & Statistics*. Redlands, CA: ESRI Press
- Newman, J 1992 'The Late Roman and Anglo Saxon settlement pattern in the Sandings of Suffolk', in Carver, M (ed) *The Age of Sutton Hoo*. Woodbridge: Boydell Press
- Oonk, S, Slomp, CP and Huisman, DJ 2009a 'Geochemistry as an aid in archaeological prospection and site interpretation: current issues and research directions'. *Archaeological Prospection* 16, 35–51
- Oonk, S, Slomp, CP, Huisman, DJ and Vriend, SP 2009b 'Effects of site lithology on geochemical signatures of human occupation in archaeological house plans in the Netherlands'. *Journal of Archaeological Science* 36, 1215–1228
- Palmer, R A 2009 'Land at Rendlesham, area centred TM324530, Suffolk: aerial photographic assessment', in Plouviez, J 2009 *Archaeological Survey Report: Naunton Hall, Rendlesham RLM 011, 012, 013, 014, 036*. Ipswich: Suffolk County Council
- Plouviez, J 2009 *Archaeological Survey Report: Naunton Hall, Rendlesham RLM 011, 012, 013, 014, 036*. Ipswich: Suffolk County Council
- Riley, D M 1987 *Air Photography and Archaeology*. London: Duckworth
- Robinson, J M and Zubrow, E 2000 'Between spaces: interpolation in archaeology', in Gillings, M, Mattingley, D and van Dalen, J (eds) *Geographical Information Systems and Landscape Archaeology*. Oxford: Oxbow Books, 65–83
- Rudnick, R L and Gao, S 2005 'Composition of the continental crust' in Rudnick, R L (ed) *The Crust*. Oxford: Elsevier, 1–64
- Schreib, J 2007 *Investigation of G-BASE Regional Soil Geochemistry over Pleistocene Till Deposits in East Anglia Using Factor Analysis*. British Geological Survey Internal Report, IR/07/057. Keyworth: British Geological Survey
- Taylor, S R and McLennan, S M 1985 *The Continental Crust: its composition and evolution*. Oxford: Blackwell
- Terry, R, Fernández, F, Parnell, J and Inomata, T 2004 'The story in the floors: chemical signatures of ancient and modern Maya activities at Aguateca, Guatemala'. *Journal of Archaeological Science* 31, 1237–1250

Tobler, W R 1970 'A computer movie simulating urban growth in the Detroit Region'. *Economic Geography* 46, 234–240

Williamson, T 2006 *England's Landscapes: East Anglia*. London: Collins

Wilson, C A, Davidson, D A and Cresser, M S 2009 'An evaluation of the site specificity of soil elemental signatures for identifying and interpreting former functional areas'. *Journal of Archaeological Science* 36,2327–2334

Woodhouse, H 2008 *Geophysical Survey of Land at Naunton Hall Rendlesham*. Cambridge: L-P: Archaeology



ENGLISH HERITAGE RESEARCH AND THE HISTORIC ENVIRONMENT

English Heritage undertakes and commissions research into the historic environment, and the issues that affect its condition and survival, in order to provide the understanding necessary for informed policy and decision making, for the protection and sustainable management of the resource, and to promote the widest access, appreciation and enjoyment of our heritage. Much of this work is conceived and implemented in the context of the National Heritage Protection Plan. For more information on the NHPP please go to <http://www.english-heritage.org.uk/professional/protection/national-heritage-protection-plan/>.

The Heritage Protection Department provides English Heritage with this capacity in the fields of building history, archaeology, archaeological science, imaging and visualisation, landscape history, and remote sensing. It brings together four teams with complementary investigative, analytical and technical skills to provide integrated applied research expertise across the range of the historic environment. These are:

- * Intervention and Analysis (including Archaeology Projects, Archives, Environmental Studies, Archaeological Conservation and Technology, and Scientific Dating)
- * Assessment (including Archaeological and Architectural Investigation, the Blue Plaques Team and the Survey of London)
- * Imaging and Visualisation (including Technical Survey, Graphics and Photography)
- * Remote Sensing (including Mapping, Photogrammetry and Geophysics)

The Heritage Protection Department undertakes a wide range of investigative and analytical projects, and provides quality assurance and management support for externally-commissioned research. We aim for innovative work of the highest quality which will set agendas and standards for the historic environment sector. In support of this, and to build capacity and promote best practice in the sector, we also publish guidance and provide advice and training. We support community engagement and build this in to our projects and programmes wherever possible.

We make the results of our work available through the Research Report Series, and through journal publications and monographs. Our newsletter *Research News*, which appears twice a year, aims to keep our partners within and outside English Heritage up-to-date with our projects and activities.

A full list of Research Reports, with abstracts and information on how to obtain copies, may be found on www.english-heritage.org.uk/researchreports

For further information visit www.english-heritage.org.uk

