Soil geochemical methods in archaeo-geophysics: exploring a combined approach at sites in Scotland

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ABSTRACT

This paper explores the application of geophysical and soil geochemical methods to detect archaeological features in three traditionally ‘difficult’ survey environments in Scotland: wind-blown sands (Bay of Skaill, Orkney), clay (Chesterhall Parks Farm, Lanarkshire) and glacial drift deposits (Forteviot, Perthshire). The results presented here are part of the first research project that systematically tested a combined approach using geophysical and soil characterisation to understand the proxy responses of known archaeological features.

First, a range of geophysical techniques (earth resistance, magnetometry, FDEM and GPR) was employed over archaeological targets. Second, the different geophysical results were considered with respect to soil chemical concentrations (total phosphate and multi-element analysis), texture, pH, conductivity, organic matter content and magnetic susceptibility from archaeological deposits, topsoil and subsoil samples.

This study demonstrates that, by focusing on the responses of single archaeological features and assessing their physical and chemical signatures, soil composition and processes involved in the ‘history’ of buried features are of importance in improving our understanding of the reasons behind their detection with geophysical means. For example, at the cropmark site at Forteviot, chemical transformations can be triggered by organic matter accumulation and increased water retention within prehistoric ditch deposits and can have an effect on the type of magnetic contrast. In addition, chemical concentrations revealing anthropogenic organic materials can explain the enhanced conductivity of theoretically impervious features, as illustrated at the Bay of Skaill site.

The study also provide insights into how a particular soil environment may affect different geophysical techniques such as the masking effects of heterogeneous glacial drift deposits or deep windblown sands. These types of survey environments characterise many archaeologically rich areas in Scotland, where integrated strategies, such as the one used in this investigation, are the best option to maximise detection of subsurface features and provide confident and augmented interpretations.

Key words (6): multi-technique geophysical survey, soil chemical analysis, soil magnetic susceptibility, soil physical characterisation, archaeological prospection, Scottish archaeology

1. INTRODUCTION

Geophysical and soil geochemical methods have been widely used to locate and interpret subsurface evidence of past human occupation in a non-destructive and minimally invasive manner (Clark, 1990; Sarris & Jones, 2000; Scollar, Tabbagh, Hesse, & Herzog, 1990). The discipline of archaeo-geophysics has played an important role in discovery and characterisation of cultural heritage assets, from single features and sites to entire archaeolandscapes (Becker & Fassbinder, 2001; Campana & Piro, 2009; Gaffney & Gater, 2003; Powlesland & Lyall, 1996; Apostolos Sarris, 2015). Geochemical methods, although adopted on a smaller scale, have also yielded valuable information on the location and extent of archaeological sites as well as investigations into past land use and activity areas (Aston, Martin, & Jackson, 1998; Bintliff, Gaffney, Waters, Davies & Snodgrass, 1990; Entwistle, Abrahams, & Dodgshon, 1998; Jones et al., 2010; Middleton & Price, 1996; Terry, Fernández, Parnell, & Inomata, 2004; Wells, 2004; Wilson, Davidson, & Cresser, 2009).

Geophysical and geochemical prospecting methods are based on very different detection and analytical principles. However, a fundamental and common requisite for their successful application is the existence of a physico-chemical contrast between the buried objects or deposits (e.g., archaeological features) and the surrounding soil environment. If sufficient contrast exists, these methods are able to map ‘anomalous’ variations of the physical properties of the ground or soil geochemical concentrations, caused by past human activity (**Figure 1**). Factors linking soil physical, chemical and biological properties, soil processes and their dynamics with different types of archaeological features are fundamental in controlling this contrast.

The effects of these soil factors on the variable results provided by geophysical and geochemical methods are still not fully understood (Armstrong, Cuenca-García, & Moffat, 2015; Oonk, Slomp, & Huisman, 2009). Some consequences of this gap in knowledge are the limitations in extracting all the information available from these datasets, constrained or vague interpretations and disappointment in the application of these methods.

This paper presents the findings of a study that explores the potential of a combined survey strategy, integrating a range of soil geochemical analyses as part of multi-technique geophysical surveys to detect archaeological features. The combined approach was systematically applied at three contrasting archaeological sites in Scotland, each one presenting specific challenges to archaeological prospection and conducted over known archaeological features. The aim of the study was to assess possible effects of soil and site setting on the results provided by the different methods in order to improve the existing understanding of the factors involved in the genesis of contrast and type of detected signatures.

2. MATERIALS AND METHODS

2.1. Study sites

Archaeological sites and targets were selected on the basis that they contained well-documented archaeological features, covered different environmental settings and presented specific challenges relating to archaeological prospection (**Figure 2**) (**Table 1**).

Bay of Skaill (Orkney): a Viking longhouse was discovered on the summit of the 'East Mound', situated near another other important focus of Viking activity, the mound of Snusgar (Griffiths, 2006). Previous gradiometer surveys at the area characterised these mounds as clusters of strong magnetic responses (Griffiths, 2011). Test trench excavations exploring a magnetically quiet area at the 'East Mound' uncovered the longhouse. A linear stone structure revealed near the longhouse during the test trenching was selected as the target for this study (**Figure 2, a**).

Chesterhall Parks Farm (South Lanarkshire): this site contains a group of Iron Age ditched enclosures that were first identified by aerial photography as cropmarks. Previous gradiometer and earth resistance surveys at the site produced inconclusive results in terms of resolving the enclosures revealed by the cropmarks (Sharpe, 2004, 181). Test trench excavations confirmed the presence of deep ditches, and they were exposed close to the surface. Finds retrieved included large amounts of cremated bone from floor layers, lead slag, ore, and in situ burning with some burnt wood (Sharpe, 2004, 186). Chemical analysis of bulk soil samples collected during the excavation showed enrichment of Zn, S, Ca and P and other depletions within the ditches as well as enhanced Ca concentration in floor samples. The targets selected at this site were the ditches of two enclosures identified by aerial photography (**Figure 2, c**).

Forteviot (Perthshire): cropmarks identified by aerial photography revealed a concentration of Neolithic to Bronze Age hengiform monuments (Alcock & Alcock, 1992). These included a massive palisaded enclosure containing an earth henge monument and other enclosures outside the palisade. The results of previous gradiometer surveys yielded very faint negative responses indicating the ditches. The results from former earth resistance surveys were similarly inconclusive. This case study targeted the ditches of an enclosure located NW of the palisade (**Figure 2, b**).

2.2. Research Methods

A research strategy combining a range of routine geophysical surveys and soil analytical methods was systematically applied at the three archaeological sites (**Figure 3**). Gradiometer, ground penetrating radar (GPR), frequency domain electromagnetics (FDEM) and/or earth resistance surveys were carried out in order to detect and characterise the geophysical response of the archaeological targets (**Table 2**). The geophysical data collected for this investigation was minimally processed in order to maintain the data as 'real' as possible. Geoplot, ReflexW & Surfer software were used for data processing and map production.

Topsoil samples were collected over the targets along a line, generally using 1 m or 0.5 m sampling intervals (depending on the size of the targeted feature). Soil was extracted at different depths according to the expected depth of the archaeological remains and topsoil interface. Open sections were carefully cleaned to take fresh samples from all visible deposits. The sampling interval was sometimes smaller than 0.5 m in order to sample small deposits visible in open sections. Soil was collected from the bottom of the section upwards to avoid contamination, and sampling tools were cleaned after collecting each sample. After removal of live organic material, soil samples were sealed in air-free plastic bags, stored in a dark environment and transferred as quickly as possible to a cold store. Sub-samples were air dried at room temperature to reduce the effects of possible chemical alterations. Air-dried soils were gently ground using a mortar and pestle and then sieved using a mechanical shaker for 5 minutes. The different soil analyses were carried out following the sequence shown in **Figure 4**.

Chemical analyses were carried out to characterise the chemical signature of the general site (topsoil samples) and archaeological deposits (open-section samples) (**Table 3**). Analyses included the determination of total (inorganic) phosphate and multi-element concentrations using an X-ray fluorescence analyser (XRF). In addition, some samples were analysed using inductively coupled plasma optical emission spectrometry (ICP-OES) to obtain further information about those elements outside the limits of detection of the XRF technique and to act as a control of the XRF results. Magnetic susceptibility (MS) was measured to identify possible anthropogenic deposits as well as to complement the geophysical information (e.g., gradiometer results). Soil texture, organic matter content (loss on ignition-LOI) and pH (and related electrical conductivity-EC) were performed during the fieldwork and at laboratory premises. The purpose of these measurements was to obtain additional information about physico-chemical properties related to the archaeological deposits and overall soil environment. The results of the different measurements on soil samples were analysed using elementary statistics. From the geochemical data, relevant enhancements and depletions were established by assessing their particular concentrations in the samples taken inside and over the features (topsoil). The results were compared to off-site controls and general backgrounds found in the literature and available databases. Relevant enhancements and/or depletions from the chemical data and other associations established from the different soil analyses were spatially compared with the geophysical responses using a GIS platform.

3. RESULTS

3.1. Bay of Skaill

The GPR and EM38 surveys carried out at this site confirmed the location of the targeted stone structure, showing that these techniques can detect relatively small linear targets in similar environments. Single GPR traverses using 450 MHz frequency antennas detected the kerbed-wall as two high amplitude reflections, sometimes with a third middle reflection, possibly caused by the infill deposits (**Figure 5**). These GPR results also provided a view of the underlying stratigraphic sequence of layered and dipping deposits.

The vertical quadrature results of the FDEM were unexpected since the stone target was, in principle, an impervious target. A fairly weak linear anomaly with a N-S orientation correlated with the location of the targeted structure (**Figure 5**). During the soil sampling, clayey and silty sand deposits were found within the stone structure. Soil analyses showed an enrichment of K, Fe, Ti (possibly as a proxy for higher clay mineral content) and general increases in MS, LOI, total phosphate and Mn, P, Rb, Ba, Cr, Li (**Figure 6**). Similar enhanced concentrations and correlations have been reported in association with organic archaeological deposits (Holliday and Gartner 2007; Wilson et al. 2007). The higher water retention capacity and related higher conductivity of these deposits seems to explain the conductive anomaly detected with the FDEM survey. The on-going interpretation is that such deposits, in association with the linear structure, may have been derived from the decomposition of an ephemeral organic wall or enclosure, probably made of peat or turf and other materials used to hold the organic blocks.

Thin layered sands and dark organic deposits including a weakly cemented iron-pan were visible in the exposed sections (**Figure 6**), extending westwards of the targeted structure as observed in the GPR results. These midden-type deposits may have been the origin of the strong magnetic anomalies recorded at the west of the target. Whilst these deposits possibly contributed to mask the targeted structure for the gradiometer survey, they also helped to reveal the presence of the archaeological area in the first instance.

3.2. Chesterhall Parks Farm

The gradiometer survey satisfactorily resolved the enclosures using a 0.5 m traverse spacing and parallel mode. The targeted enclosures were detected as two and three ring-like weak positive magnetic anomalies showing magnetically enhanced ditches (**Figure 7**). This survey also revealed other internal anomalies that may be related to structures or functional areas within enclosure 1. In any case, these magnetic anomalies were still fairly weak. Given the general low MS values of the clay matrix, frequent waterlogging of the area, and zones with strong geological magnetic responses (possibly caused by localised accumulation of varied glacial deposits), it is possible that the magnetic contrast was partially masked by these mixed effects. The slopes of Tinto Hill are mantled by frost-weathered detritus that has been extensively soliflucted (Ballantyne, 1993). The magnetic noise distinguishable in the north of the survey area may be caused by this soliflucted material. In spite of the conductive clay soils, the 225 MHz frequency GPR survey provided useful information relating to the total depth of the ditches (up to 1.20 m). The results of the 450 MHz frequency antenna survey were heavily affected by signal attenuation, but the survey managed to receive some reflections produced by the uppermost fill deposits of the ditches (~0.25 m). The quadrature component of the FDEM survey in vertical dipole showed potential to detect the ditches (**Figure 7**). The thickness and soil physical composition of these ditch deposits may explain their detection by the quadrature component (conductivity) of the FDEM survey.

Despite the landowner’s restrictions on opening a trench to expose and sample the ditches, consent was granted for localised soil sampling using an auger up to 0.5 m depth. Taking into account that this site was rarely ploughed, the shallow archaeological deposits, and other metallurgical activities previously documented at the site, it was expected that the results of the soil analysis would be fairly informative. However, the results yielded only a slightly enhanced concentration of Pb and P (in agreement with the previous soil analysis) and a high variability in the concentration of other elements in the samples taken above the ditches (**Figure 8**). The pattern observed in the later results seems to be produced by the truncation of the natural deposits by the ditches. Whilst there was a slight MS enrichment approaching the centre of enclosure 2, it is not completely certain that this enhancement would have been able to pinpoint the location of the enclosure in a more extensive survey (**Figure 9**).

3.2.1. Forteviot

The gradiometer survey resolved only the enclosure when the traverse spacing was reduced to 0.25 m in parallel mode. This technique revealed two concentric negative magnetic anomalies: an outer ditch and a segmented, less coherent inner ditch (**Figure 10**). After topsoil stripping, this survey was repeated and revealed sharper anomalies due to the enhanced magnetic contrast, which had been slightly masked by the topsoil (**Figure 10**). The topsoil contained magnetic stony material derived from intense ploughing of the underlying glacial parent material. This resulted in ‘noisy’ datasets that obscured the contrast between the ditch deposits and surrounding soil.

There was no MS enhancement or enrichment of common anthropogenic trace elements in the ditch deposits, which partially explains the characteristic negative magnetic response instead of the more usual positive response (**Figure 11 & 12**). The ditches at Forteviot were associated with a ritual site, so their deposits were not subjected to continuous anthropogenic input as at settlement sites. Soil samples from the outer ditch showed slight general depletions of major elements (e.g., Fe, **Figure 11**), as well as a discrete Mn depletion and LOI peak (deposit 1, **Figure 12**). These results point to mineralogical changes inside the ditch that led to the relatively low MS values of the ditch deposits compared to the higher MS of the topsoil and the even higher MS of the subsoil (hence negative contrast), thereby contributing to their negative magnetic responses.

The high percolation rate of the sandy top/subsoil at Forteviot and the general dry conditions hampered several attempts to conduct resistance surveys during this investigation and previous surveys. Soil saturation conditions were necessary to successfully complete the survey and reveal a single concentric low resistance anomaly (outer ditch) and a central pit-like low resistance anomaly (**Figure 10**). The latter proved to be an unusual triple cist burial. A higher capacity of these features to retain water explains their detection. This may have been triggered by a higher organic matter content inside these features.

In the case of the outer ditch, a discrete LOI peak of the uppermost ditch deposits (deposit 1, **Figure 12**) may reflect an increased biomass of crops roots at this depth, hence the higher moisture retention. This seems coherent with the depleted total P, K, and Ca values of ditch samples collected at the same depth (**Figure 11**), as result of a higher uptake by crop roots at this point.

The quadrature response of the FDEM survey produced a similar anomaly to the earth resistance technique: a subtle single concentric conductivity trend (the outer ditch) and a central pit-like anomaly (**Figure 10**). The higher ground moisture content after the heavy rain before the survey could have increased the contrast in the same manner as in the earth resistance survey. The in-phase response was also very weak and the trend again showed a single circular anomaly. Although the responses of both components were fairly weak, the quadrature component in vertical mode of the FDEM survey demonstrated potential in identifying archaeological features expected at c. 0.5–1 m, since the noise created by the plough layer was outside the maximum sensitivity range of the instrument.

The GPR survey produced the most informative results, as it gave depth estimation, high resolution mapping, and an approximate truncation level of the ditches. The survey revealed two concentric high amplitude anomalies (outer and inner ditches), both visible in the reflection profiles and the time-slices (**Figure 10**). The outer ditch showed strong reflections towards the base and innermost side of the ditch cut. Here, the cut of the ditch lies at a greater angle, and the sands and gravels were more cemented or indurated. The strong high amplitude reflections of the outer ditch correlates with this sudden change in soil texture. The samples taken over the outer ditch showed a greater variation in chemical composition, particularly at the innermost side of the ditch. This type of response may reflect a mineralogical change given the presence of the ditch, and a similar response was also observed in Chesterhall Parks.

4. DISCUSSION

From the results of this combined approach at the three study sites, some general observations relating to specific effects of the soil environment on the geophysical results are considered in this section.

Heterogeneous glacial drift deposits

Many of the superficial deposits that form the parent material of contemporary Scottish soils are characterised by Quaternary glacial drift deposits. These contain, inter alia, mixtures of sands, gravels, silts and weathered rocks carried by glaciers and dropped as the ice sheet advanced or receded. These extremely heterogeneous deposits also reflect the great diversity of rock types that characterise the geology in Scotland. The sites studied in this investigation lie over sedimentary rock belonging to different groups of the Old Red Sandstone formation (ORS), which is widespread in Scotland, some containing volcanic rocks between their varied components. At these sites, the bedrock did not directly hamper the geophysical detection of the targeted features. However, the glacial drift superficial deposits of Chesterhall Parks and Forteviot seem to have a more significant effect on the different datasets, particularly those from the gradiometer surveys. These very heterogeneous deposits may contain a great variety of rock debris that may add background noise, mask the contrast for magnetic techniques or contribute to the detection of negative magnetic anomalies (e.g., Forteviot).

Table 4 shows a summary of the results of some of the soil topsoil analyses carried out at the study sites. The brown earth and clay soil from Forteviot and Chesterhall respectively are developed from reddish and coarse sands and gravels with variable amounts of sands, silts and clay. ORS rock types are characterised by hematite (αFe_2O_3) as the main Fe-oxide, which gives the rocks their characteristic red colour (Wilson, 1971). The diversity of igneous and metamorphic rock components that ORS formations may contain also contributes to the high variability in MS of the parent material from which soil develops in different areas of Scotland. From the means taken at the case study sites, the highest MS values are from the coarse and acidic brown earth from Forteviot. Such coarse and freely draining texture and acidic pH are characteristic of Scottish soils. However, the clay soil at Chesterhall Parks Farm and the alkaline soils at the Bay of Skaill were both characterised by fairly low MS values (Error! Reference source not found.**)**.

Glacial geomorphology

The glacial past also had an important role in shaping the present day Scottish landscape by developing intricate combinations of erosional and depositional geomorphological features and landforms. This is illustrated at the sites surveyed in this study: outwash terraces in Forteviot and hillslope solifluction processes in Chesterhall Parks Farm (**Table 1**). These landforms may have an effect on the results of the surveys by introducing clusters of magnetic noise (as in the case of Chesterhall Parks Farm) or adding a high signal variability in the datasets. Geomorphological features associated with glacier landscapes (e.g., kames, eskers, drumlins or ice wedges) may be taken into consideration when interpreting geophysical datasets of Scottish sites. Solutions to distinguish these landscape features from those of archaeological interest could include soil chemical characterisation, in a similar combined manner as used in this study but at a larger scale.

Soil additions and translocations

Archaeologically rich coastal areas in Scotland are often characterised by sites concealed under high-energy deposits of fine-grained sands developed by aeolian processes, as illustrated at the Bay of Skaill. These sands are expected to have high concentration of Ca due to the calcium carbonate of the shells from which they were partially derived and the generally low MS values (**Table 4**). The low MS values are due to the main constituents of the sands, silica ($SiO2$) in the form of quartz, and calcium carbonate ($CaCO3$), which are diamagnetic materials (Maher & Hounslow, 1999; Moskowitz, 1991). Cut features presenting enhanced MS fill deposits may be detected, for example, with a gradiometer survey. However, archaeological features covered under thick aeolian deposits may be out of reach for this technique. The surveys carried out at the Bay of Skaill demonstrate the potential of GPR and FDEM survey to detect structural features in relatively deep wind-blown sands. Although the gradiometer did not detect any structural features at the site, it proved useful in identifying the midden deposits located near the Viking long-house. Whilst natural mounds may show homogenous and magnetically quiet sand deposits, anthropogenic mounds may be expected to be magnetically noisy. Therefore, this technique can still be useful in exploring mounds of potential archaeological importance by identifying magnetically noisy areas associated with anthropogenic deposits and thus revealing former human occupation.

Soil processes may develop localised hill/terrace slope deposits, such as the soliflucted fine-grained clays and colluvial volcaniclastic material at Chesterhall Parks Farm, that may not correspond to the deposits indicated in soil maps or available databases. These deposits are the result of the gradual accumulation of fine weathered material that moved slowly downslope from the nearby Tinto Hill, induced by gravitational forces on saturated sediments and as a result of Periglacial/Postglacial conditions. The deep clay at this site explains the frequent waterlogged conditions at a site mapped as freely draining brown earth in the soil maps. Despite the high conductivity of clay soils and the magnetic noise introduced by the igneous material, the targeted enclosures at the site were detected to a relative degree by geophysical means.

Soil texture & related water content capacity

Coarse sandy soils drain water more quickly than finer clayey soils. Arable coarse soils with a thin litter layer overlying a freely draining sand or gravel subsoil can produce very high resistance values, which may not be suitable for earth resistance surveys during the Scottish summer time, as was the case at Forteviot. Soil textural variations in the cementation of the sands and gravels of the innermost cut of the ditch may have also contributed to the strong GPR reflections detected in Forteviot.

The higher number of micropores in clay soils cause retention of water, whilst the lack of macropores limit water infiltration rates, causing waterlogged conditions (Schaetz & Anderson, 2005). Although such conditions can saturate and mask soil conductivity contrast, the GPR (particularly with the low frequency antenna) and FDEM survey (quadrature in vertical mode) carried out at Chesterhall Parks Farm provided some results. This was possible given the thickness and shallow buried ditches.

Fe-content & related MS

Determination of the iron content in soil, if combined with MS analysis, may give an idea of the magnetic background and state of the iron oxides present at the survey environment. **Table 4** shows the relatively high Fe concentrations in topsoil samples in the case study of Forteviot and Chesterhall Parks Farm sites. This may reflect the impact of the acidic parent material from which these soils develop (Phillips, 2007). However, high Fe concentration in soil does not always correlate with high MS; at Chesterhall Parks Farm, despite high Fe contents, the MS values are fairly low due to the frequently waterlogged conditions at this site. However, more important is the determination of Fe and MS of topsoil, subsoil and archaeological deposits because this helps to elucidate the complex factors of contrast and detection of archaeological features at the sites. For example, these analyses were fundamental in understanding the magnetic reversal of the ditches detected at Forteviot.

Organic matter & related water content capacity

Variation in water retention was the main factor for contrasts in conductivity properties of the targeted features and their consequent detection with the earth resistance, FDEM and GPR surveys at the three sites. At Forteviot and Bay of Skaill, the capability of the targeted features to retain water correlates with their higher organic content. In soils, water retention increases with increasing clay content and organic matter because of the affinities of water for those solids (Schaetz & Anderson, 2005).

Organic matter, water content & related chemical transformations

Although the chemical analytical techniques used in this investigation (pXRF and ICP-OES) did not identify chemical forms, they allow an estimate of soil mineralogical transformations involved in the contrast and type of geophysical response detected at several sites. Chemical transformations can be triggered by organic matter accumulation and water retention in soils. For example, reductive dissolution of Mn and Fe oxides can occur due to the decomposition of organic matter and contribute to the release of metals and magnetisation of sediments (Lovley, 1991; Orgeira & Compagnucci, 2006). According to Weston (2002), prolonged waterlogged conditions can transform ferric material to less magnetic and more dissolvable ferrous forms. The effect of reductive dissolution of these oxides has also been suggested as the cause of Fe and Mn depletions in archaeological floor deposits (Oonk, Slomp, Huisman, & Vriend, 2009). The depleted values in Mn, Fe and MS seen in this study in association with ditch features in Forteviot are likely to be the results of reduction dissolution processes and to have contributed to the detection of negative magnetic anomalies. The higher organic content and related higher capacity of the outer ditch to retain water, seen also in the depletion of Mn and in the LOI peak (**Figure 11**), may represent a discrete reductive zone that may favour dissolution of Fe-and Mn oxides and consequent lower susceptibilities.

5. CONCLUSIONS

The study demonstrates that, by applying both geophysical and geochemical methods, ‘traditionally difficult’ survey environments for some geophysical techniques can be prospected in a satisfactory manner. This combined approach can be very valuable in order to provide a more reflective analysis about how local geological and pedological settings influence the geophysical results. For example, many archaeological survey environments in Scotland are characterised by highly variable drift soil deposits that originated from the effect of past glacial processes, weathering a great diversity of rock types. In such conditions, surveys based on a single-technique (e.g., magnetometer surveys) have a high chance of being disappointing given the subtle contrast of magnetic properties and unanticipated magnetic signatures as seen in Forteviot. In the case of aeolian environments, these sand deposits characterise many archaeologically rich coastal areas in Scotland. This investigation shows that anthropogenic organic deposits related to past human occupation can be detectable by sometimes unexpected geophysical techniques, as in the case of the Bay of Skaill.

The study shows that a detailed analysis of particular archaeological features can help to identify specific soil properties and processes, inside or outside the features, which are behind the contrast detected (or not) by the different geophysical techniques. Successful or failed detection of the targets by geophysical means involves ‘case specific’ variables such as soil properties, ground surface and temporal climatic variations, and depth of burial of archaeological features. The investigation showed that different types of archaeological features (a wall foundation or a ditch) can provide unpredicted geophysical signatures given the effect of complex contrast dynamics and post-depositional processes that develop inside features. The effects of soil materials and properties, such as texture (grain size and cementation), and particularly organic matter content and its related water retention capabilities, were fundamental to resolve the targets with electrical and electromagnetic methods. The composition of soil parent material and chemical transformations triggered by organic matter accumulation (e.g., reduction dissolution of Fe- and Mn-oxides) can influence and be fundamental in understanding the results of magnetic methods.

The study also allowed a detailed observation of the geochemical signatures of shallow anthropogenic targets from topsoil samples and fill deposits. Some of these signatures included rather unusual responses, such as general depletions of typical crop macronutrients (e.g., P, K, Ca) and a high variability of the chemical concentrations of major elements obtained from the ditch features.

To summarise, the integration of geochemical soil analysis as part of geophysical prospection can contribute to an understanding of how soil settings of a site may affect the results of different geophysical techniques and thus allow improved interpretations. The drawback of such combined approach is that it is time-consuming and demands expertise.

In the current framework of fast-moving geophysical surveys, research efforts leading to technique reappraisal and improved data interpretation should encompass large-scale surveys and data production. To do this, well-thought-out soil sampling strategies should be coordinated within geophysical surveys taking into account the time and skilled personnel required to sample in an accurate manner. Additionally, the correct storage of soil samples and soil processing before analysis should be carefully planned. Features exposed during archaeological excavations provide a unique opportunity not only to validate the geophysical results but also to explore particular responses through soil analysis in a similar manner as shown in this study. In return, the results can contribute to enhanced archaeological interpretation of such features. Therefore, closer collaboration among archaeologists should be sought in order to gain access to exposed features for soil sampling and measurements.

In the wide variety of soil systems, there is not a single factor that can explain the detection of geophysical anomalies of archaeological significance, nor is there a "magic" technique able to detect them regardless of the soil environment. Soil materials, properties and post-burial soil formation processes are inherently related to archaeological features and their proxy detection, and they have to be considered simultaneously. Despite the extra effort in acquiring and analysing complementary soil data, it is crucial to continue developing strategies to incorporate soil analysis within large scale geophysical surveys in order to improve data interpretation and advance in the discipline of archaeological geophysics in a balanced manner.

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Tables

Table 1: Archaeological targets and general settings at the study sites

Site	Challenge	Target	Bedrock	Superficial Deposits	Soil	Geomorphology	Field Use
Bay of Skaill (Orkney)	– Viking longhouse concealed under deep windblown sands. – Gradiometer surveys did not detect any structural anomaly indicative of the longhouse.	– Linear Stone structure. – N-S direction. – ~1 m wide. – Deep: revealed at least 1 m deep during trial trenching.	Sedimentary (Lower Stromness Flagstone-Old Red Sandstone, mid-Devonian): laminated, carbonate-rich siltstones and shales with fine-grained and thinly bedded sandstones	Pale brown and fine-grained windblown sands (Quaternary)	Well drained and deep calcareous Regosols (Fraserburgh series)	Mound of free sand	Pasture
Chesterhall Parks Farm (South Lanarkshire)	– Grassmarks evidence of Iron Age ditch enclosures buried in highly conductive soil environment. – The results of gradiometer and earth resistance survey were inconclusive in resolving	– Concentric ditched enclosures. – Deep ditches (~up to 1 m deep. – Shallow: uppermost fill deposits were revealed to be fairly shallow during trial trenching.	Sedimentary (Wiston Grey Volcaniclastic Sandstone-Old Red Sandstone, early Devonian): fine-to coarse-grained volcaniclastic sandstones of greenish-grey ashy colour (Browne et al. 2002)	Clyde Valley fluvioglacial deposits (Quaternary)	Deep and poorly drained heavy clay (confirmed by test trench excavations (Sharpe, 2004)	Outwash and river terrace	Pasture and very occasionally ploughed (landowner comment)

	the enclosures.							
Forteviot (Perthshire)	– Cropmarks evidence of Neolithic to the Bronze Age henge enclosures.	– Shallow	Sedimentary (Arbuthnott-Garvock Group-Old Red Sandstone): sandstones, conglomerates, shales, mudstones and volcanic rocks (Browne et al. 2002)	Glacio-fluvial sand and gravel deposits (Quaternary)	Well drained reddish-brown earths (Gleneagles series)	Solifluction terrace	Arable (barley crops at the time of this study)

Table 2: Summary of the geophysical techniques and surveys parameters used at the study sites

Technique	**Instrument**	**Sampling**		
		Bay of Skaill	**Chesterhall Parks**	**Forteviot**
Gradiometry	Bartington Grad 601-2	0.5 m traverse & 0.125 m in-line (parallel mode)	0.5 m traverse & 0.125 m in-line (parallel mode)	– 0.5 m traverse & 0.125 m in-line (parallel mode). – 0.25 m traverse & 0.125 m in-line (parallel).
Ground Penetrating Radar (GPR)	Sensors & Software PulseEKKO 1000	Single GPR lines (450 and 225 MHz): 0.05 m and 0.10 m in-line, time-window=80 ns and 120 ns	Single GPR lines (450 and 225 MHz): 0.05 m and 0.10 m in-line, time-window=60 ns and 100 ns	– High resolution survey (450 MHz): 0.25 m traverse & 0.05 m in-line, parallel & step mode, time window=150 ns, stacks=16, samples=200 ps. – Single GPR lines using 450 MHz: 0.05 in-line, time-window=60 ns.
Frequency Domain Electromagnetics (FDEM)	Geonics EM 38 (+GPS)	1 m traverse (parallel, vertical dipole, in-phase & quadrature component)	1 m traverse (parallel, vertical dipole, in-phase & quadrature component)	1 m traverse spacing (parallel, vertical dipole, in-phase & quadrature component)

Earth Resistance	Geoscan RM15	0.5 m traverse & 0.5 m in-line (1 m probe spacing) (zigzag mode)	0.5 m traverse & 0.5 m in-line (0.5 probe spacing, zigzag mode)	0.5 m traverse & 0.5 m in-line (0.5 & 1 m probe spacing, zigzag mode)

Table 3: Geochemical methods used to analyse the soil samples collected at the study sites.

Analysis	Digestion	Procedure	Instrument
Total (Inorganic) Phosphate	Ignition-HCl	– Molybdenum blue colorimetric method (SASSA)	Fisherbrand colorimeter (Archaeology, University of Glasgow)
XRF	Not required	– Multi-element concentration analysis of 33 elements: Mo, Zr, Sr, U, Rb, Th, Pb, Se, As, Hg, Au, Zn, W, Cu, Ni, Co, Fe, Mn, Cr, V, Ti, Sc, Ca, K, S, Ba, Cs, Te, Sb, Sn, Cd, Ag, Pd – Soil samples were transferred into a plastic cup and covered with polypropylene X-ray film TF-240 FLUXANA. – A shielded lead box stand was used for protection. – A helium purge device was used to increase instrument sensitivity to lighter elements. – Each sample was measured for *c*.2 minutes. – Measurements were repeated after slightly rotating the sample cups and were averaged. – Calibration checks were done using two international standards (TILL-4 and NIST 2780), a random sample and a blank sample. – The accuracy test gave generally good results for the majority of elements except for S, V and Rb. The concentrations of V and Rb were found to be slightly overestimated.	Thermo Scientific Niton XL3t GOLDD (Archaeology, University of Glasgow)
ICP-OES	HF/HCl/HNO3 mixture using a CEM Mars Xpress microwave digestion system	– Multi-element concentration analysis of 18 elements: Al, Fe, Na, K, Ca, Mg, Ti, P, Mn, Ba, Sr, Pb, Cu, Zn, Cr, Ni, Li, and Co – Measurements were evaluated using an external calibration and scandium as an internal standard. – Certified reference material (MESS-3) was used to monitor the quality of the analytical process.	Varian Vista Pro (Scottish Alliance for Geosciences, Environment and Society-SAGES facility,

		– With each batch of samples, two procedural blanks were run to control blank levels and variability.	University of Edinburgh)
Magnetic Susceptibility	Not required	– The samples were transferred into pre-weight 10 cm3 plastic cups. – Samples were weighed in order to calculate mass-specific (χ) MS. – Before the measurements, the instrument was left to stabilise. – Samples were measured at low frequency (χlf=0.46 kHz) and at high frequency (χhf=4.6 kHz) to calculate frequency-dependent mass susceptibly (χfd) in percentage. – MultiSus software was used to take the measurements. – Instrument calibration and accuracy was assessed by measuring two standard samples, ST1 (ferrimagnetic) and H_2O.	Bartington MS2B (University of Glasgow)

*Table 4: Summary of the mean results of the physical and chemical analysis of the topsoil samples collected at the three case study sites. Most of the results show the in-site and off-site (controls) values. A * signifies not analysed.*

		Bay of Skaill		**Chesterhall Parks Farm**		**Forteviot**	
Site		Viking Settlement (positive/impervious feature)		Prehistoric Enclosure (cropmark)		Prehistoric Enclosure (cropmark)	
Soil		Calcareous Regosol		Clay		Brown earth	
Soil Texture		Fine-grained sands with some shell fragments		Clay with some gravels		Stony sandy loam	
pH (In-site)		9 (Strong alkalinity)		6 (Medium acidity) to 5 (Strong acidity)		6.5 (Very slight acidity)	
EC (µs) (In-site)		100		107		54	
LOI (%) (In-site)		0.061		0.031		0.029	
In/Off-site		**In**	**Off**	**In**	**Off**	**In**	**Off**
Total P (µg/kg)		155		99	125	243	271
pXRF (mg/kg)	Fe	11 933	*	23 995	22 182	26 416	26 015
	Mn	308	*	287	478	791	749
	Ti	1 456	*	4 944	4 747	5 653	5 336
	K	13 955	*	10 133	12 545	13 189	12 608
	Ca	14 8313	*	7 573	5 256	9 416	8 518
MS ($10^{-8} m^3 kg^{-1}$)		7	*	21	48	144	151

Figures

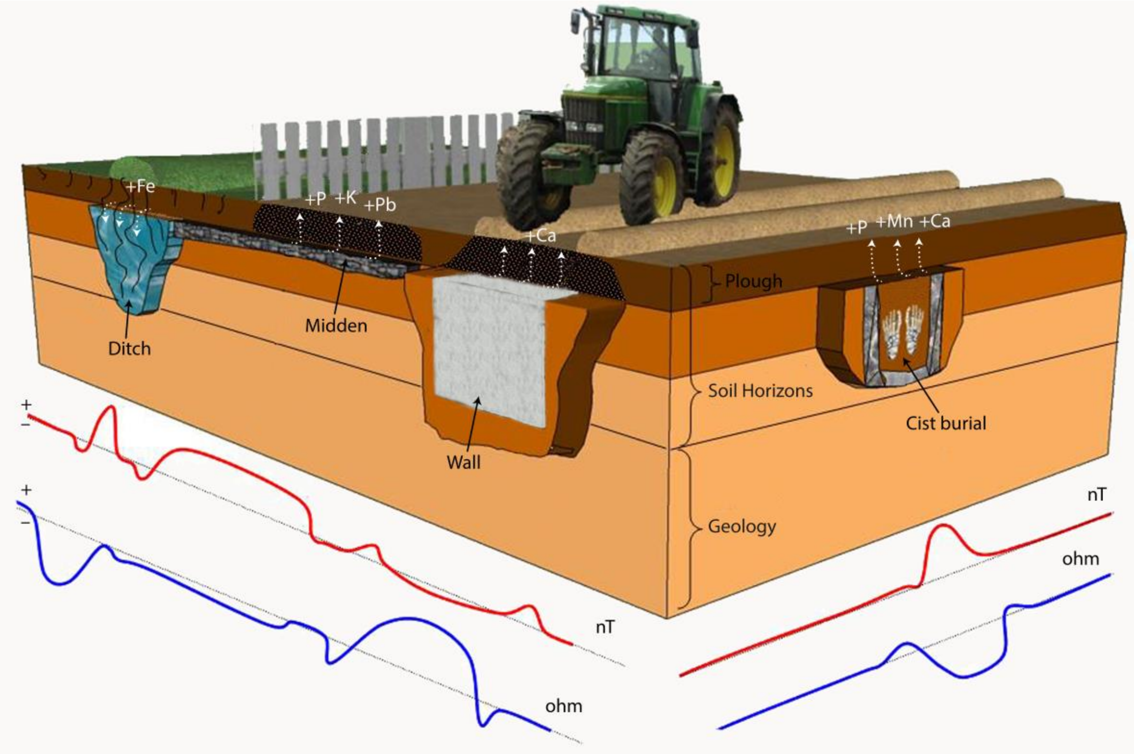

Figure 1: Diagram showing idealised geophysical and geochemical responses of common archaeological features. The magnetic response is shown in red and the earth resistance in blue (© Carmen Cuenca-Garcia).

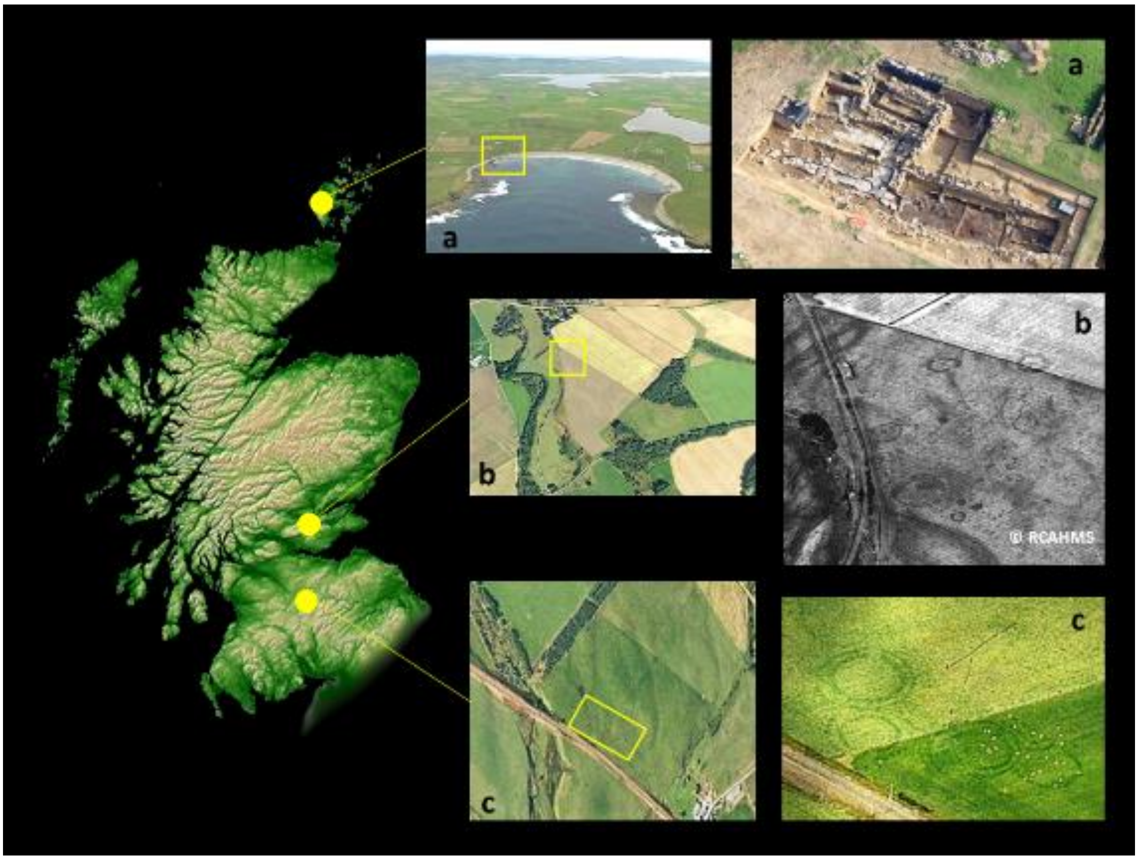

Figure 2: Location of the three study sites and general views of the survey areas (a: Bay of Skaill, Orkney, b: Forteviot, Perthshire, c: Chesterhall Parks Farm, South Lanarkshire)

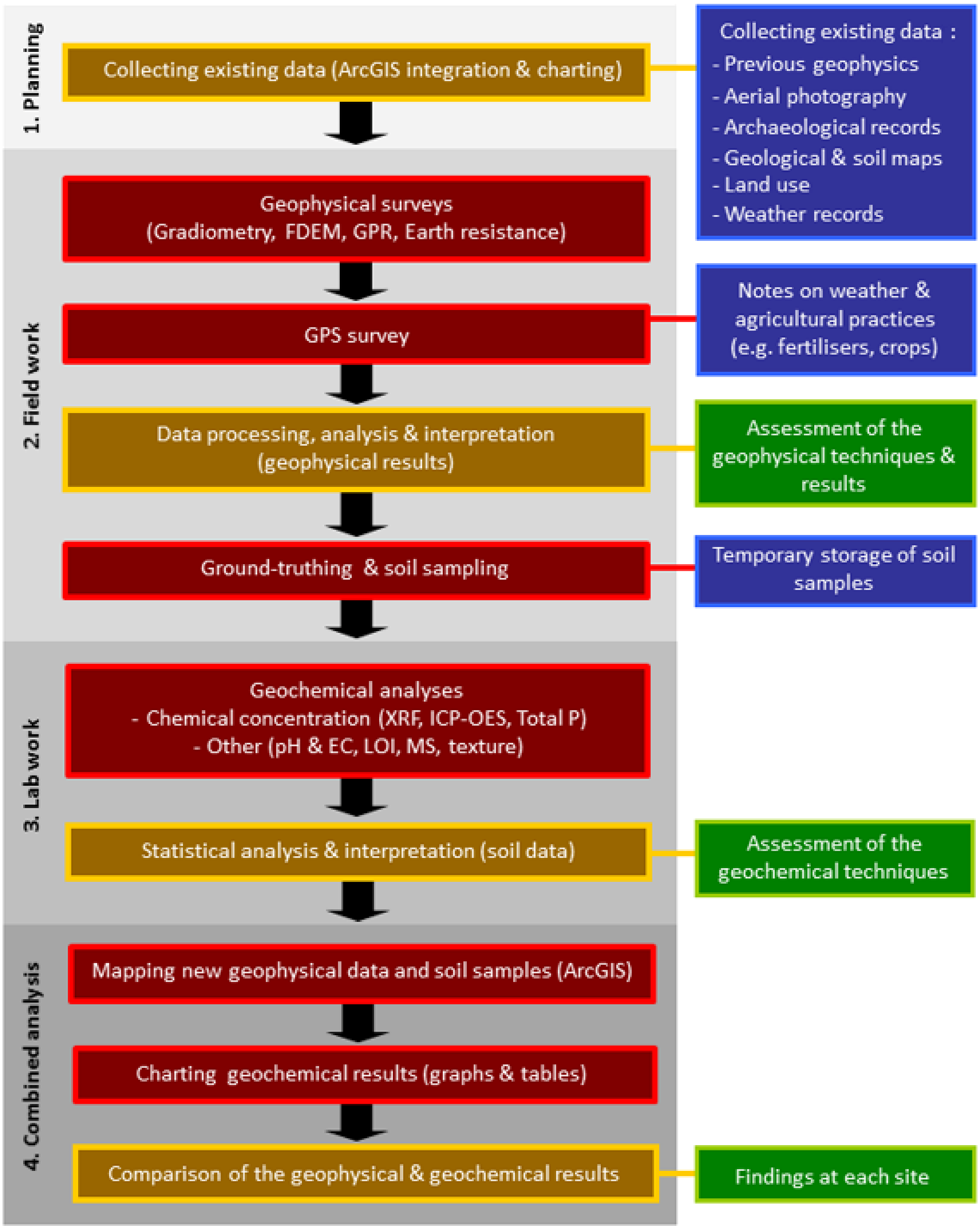

Figure 3: Diagram showing the combined research strategy in four phases. Geophysical, geochemical and other methods are in red, analytical stages are in brown, 'satellite' data collection is in blue, and the expected outcomes are in green. The acronyms are defined as follows: frequency domain electromagnetic (FDEM), ground-penetrating radar (GPR), global positioning system (GPS), X-ray fluorescence (XRF), inductively coupled plasma optical emission spectrometry (ICP-OES), total phosphate (Total P), electrical conductivity (EC), loss on ignition (LOI) and magnetic susceptibility (MS).

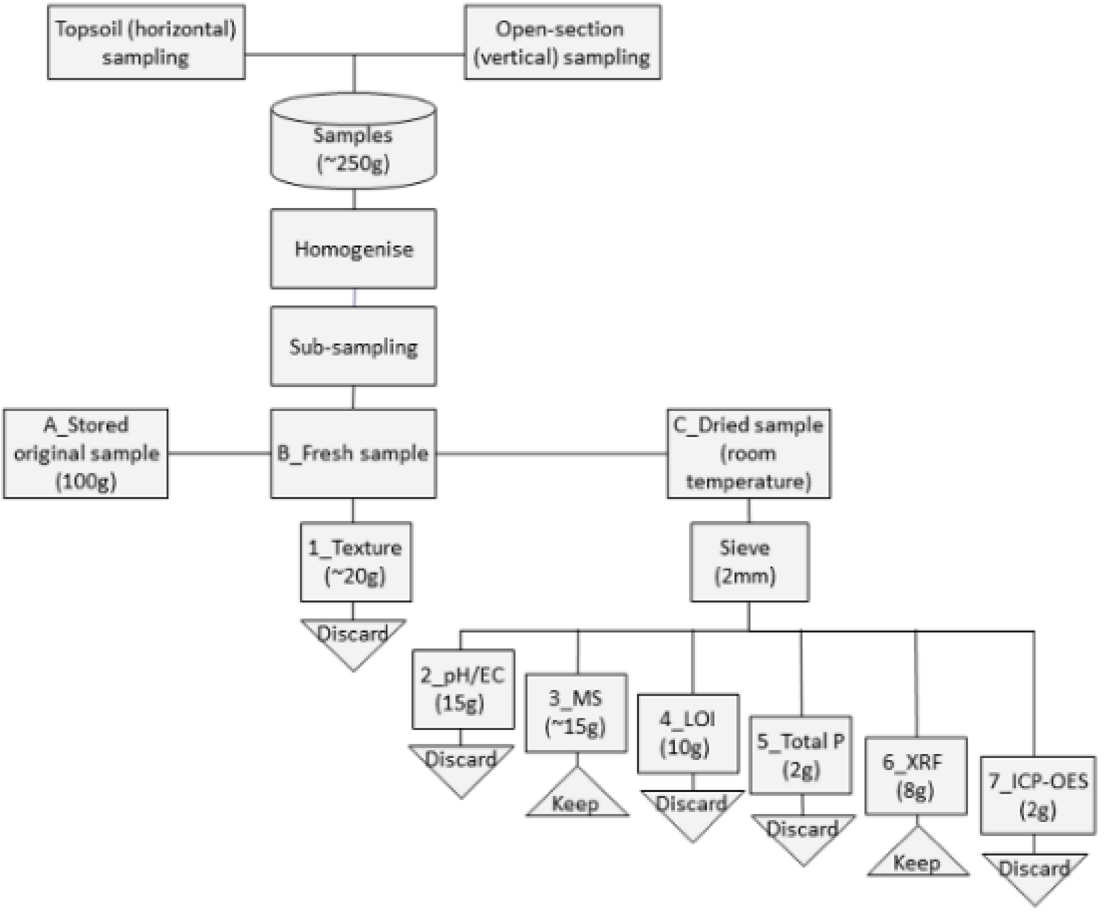

Figure 4: Flowchart showing the plan followed to carry out the soil analyses. The different analyses were performed following the Soil Analysis Support System for Archaeology-SASSA (University of Stirling) standard analytical methods and other adapted protocols from the Department of Archaeology (University of Glasgow) and the Scottish Alliance for Geosciences, Environment and Society-SAGES (University of Edinburgh). The acronyms are defined as follows: electrical conductivity (EC), magnetic susceptibility (MS), loss on ignition (LOI), total phosphate (Total P), X-ray fluorescence (XRF) and inductively coupled plasma optical emission spectrometry (ICP-OES).

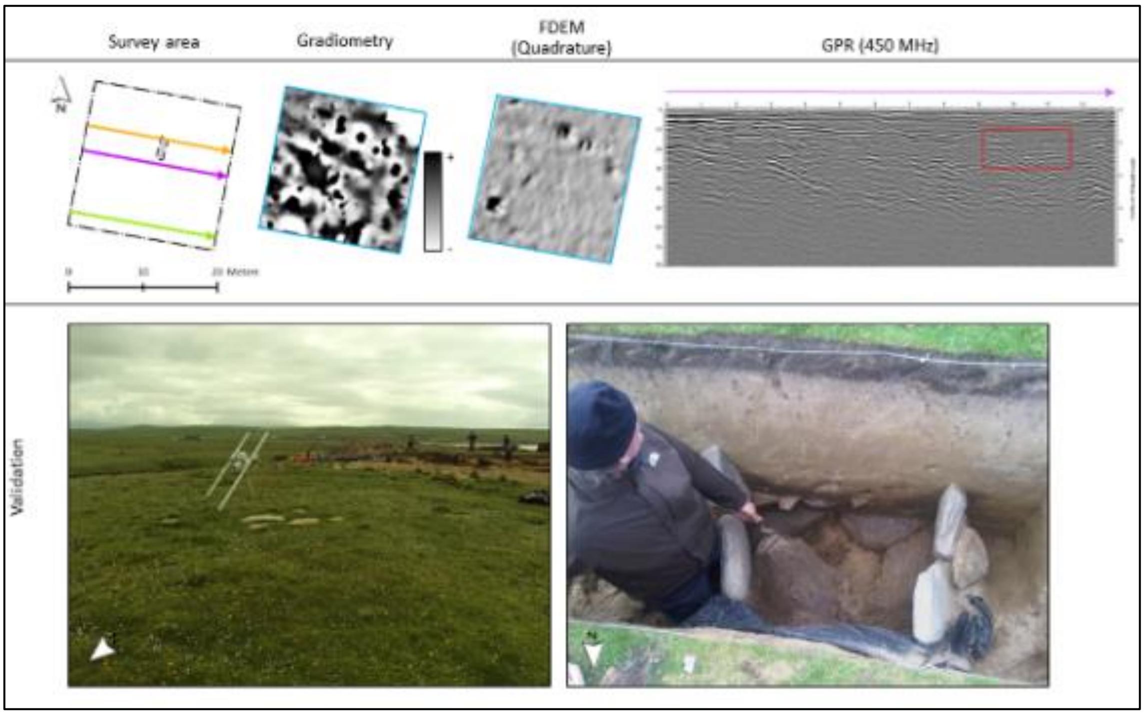

Figure 5: Results of the multi-technique geophysical survey at the Bay of Skaill, survey area and excavated target. The coloured arrows within the survey area show the location of the collected GPR profiles. The gradiometer data were plotted at 10 (black)/-10 (white) nT. The FDEM (quadrature) plot shows higher and lower values (mS/m) in black and white, respectively. High and low amplitudes in the GPR reflection profile are shaded in black and white, respectively.

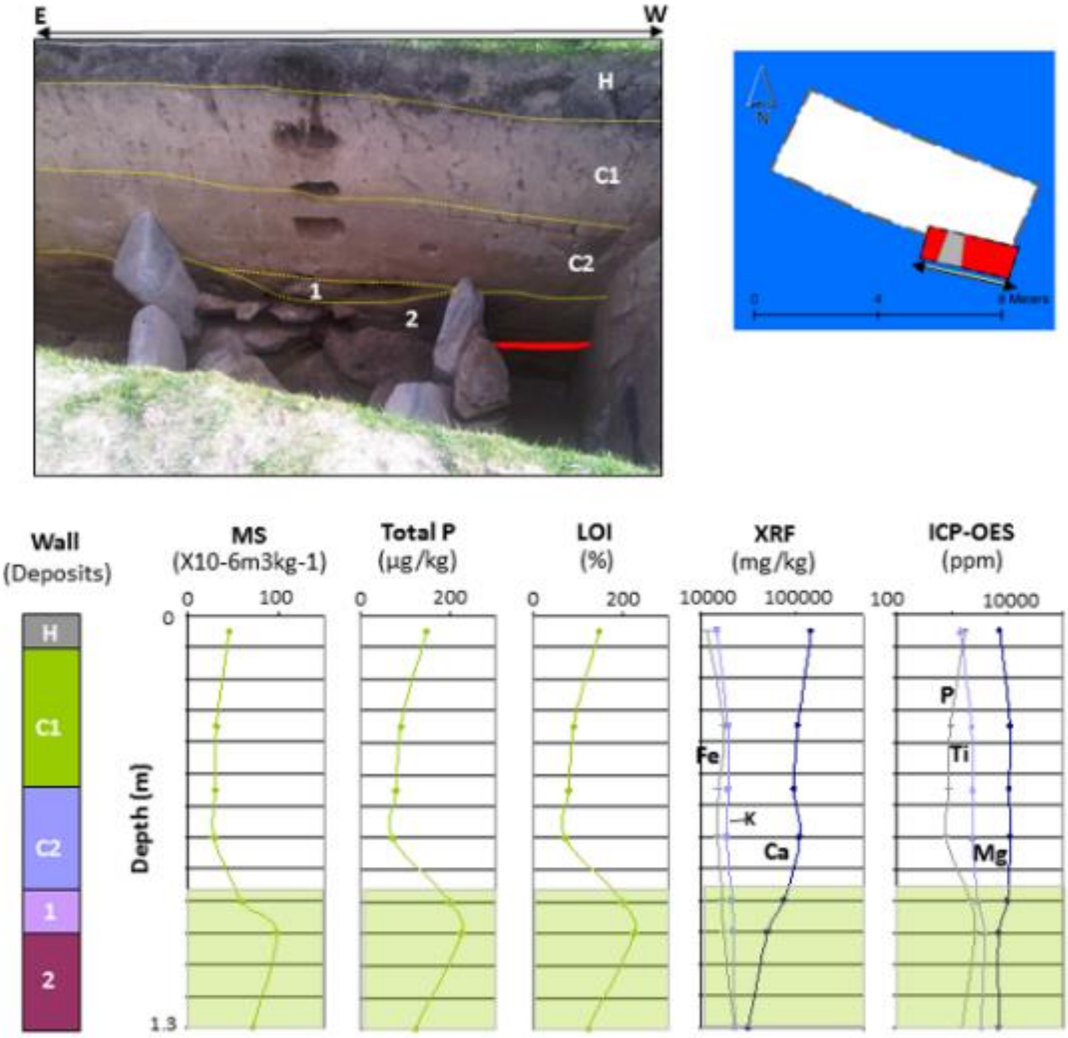

Figure 6: Selected results of the soil analyses of the samples collected from the exposed north facing section at the Bay of Skaill. The picture of the exposed section (top left) shows the location of a weakly cemented iron-pan deposit (in red).

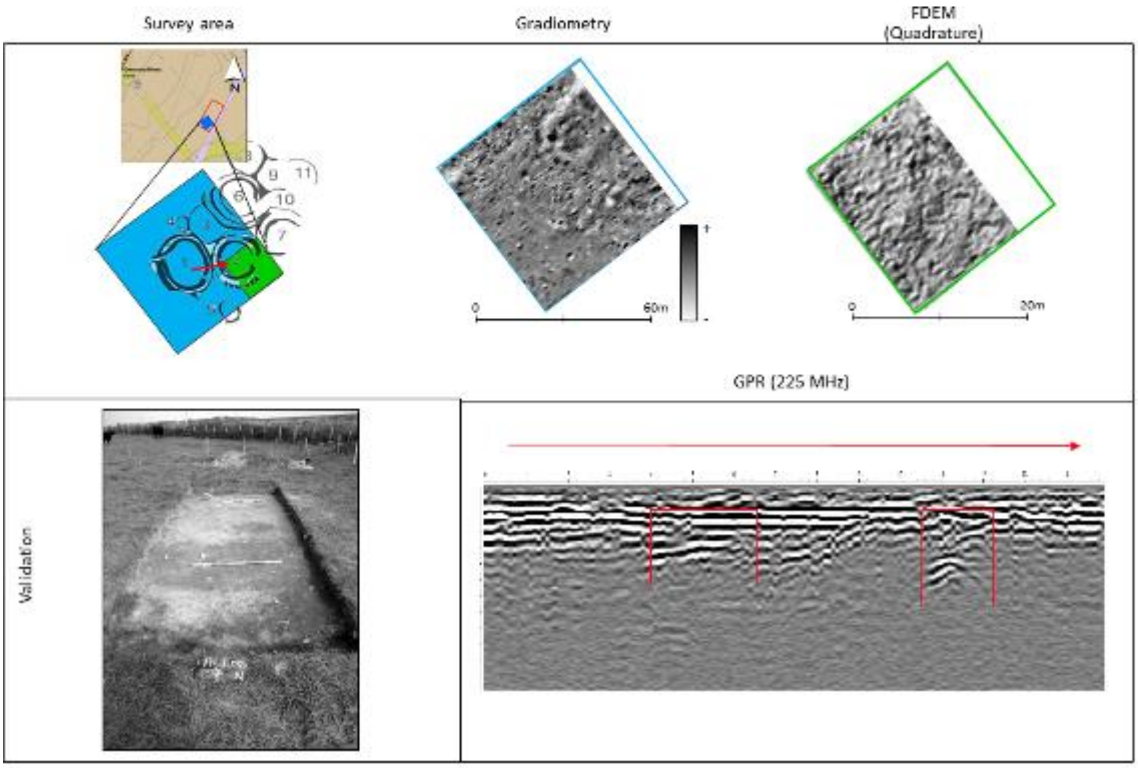

Figure 7: Results of the multi-technique geophysical survey at Chesterhall Parks Farm. The picture (bottom left) shows the ditch (enclosure 2) exposed during previous test trench excavations (L. Sharpe photographic archive). The gradiometer data were plotted at 10 (black)/-10 (white) nT. The FDEM (quadrature) plot shows higher and lower values (mS/m) in black and white, respectively. High and low amplitudes in the GPR reflection profile are shaded in black and white, respectively.

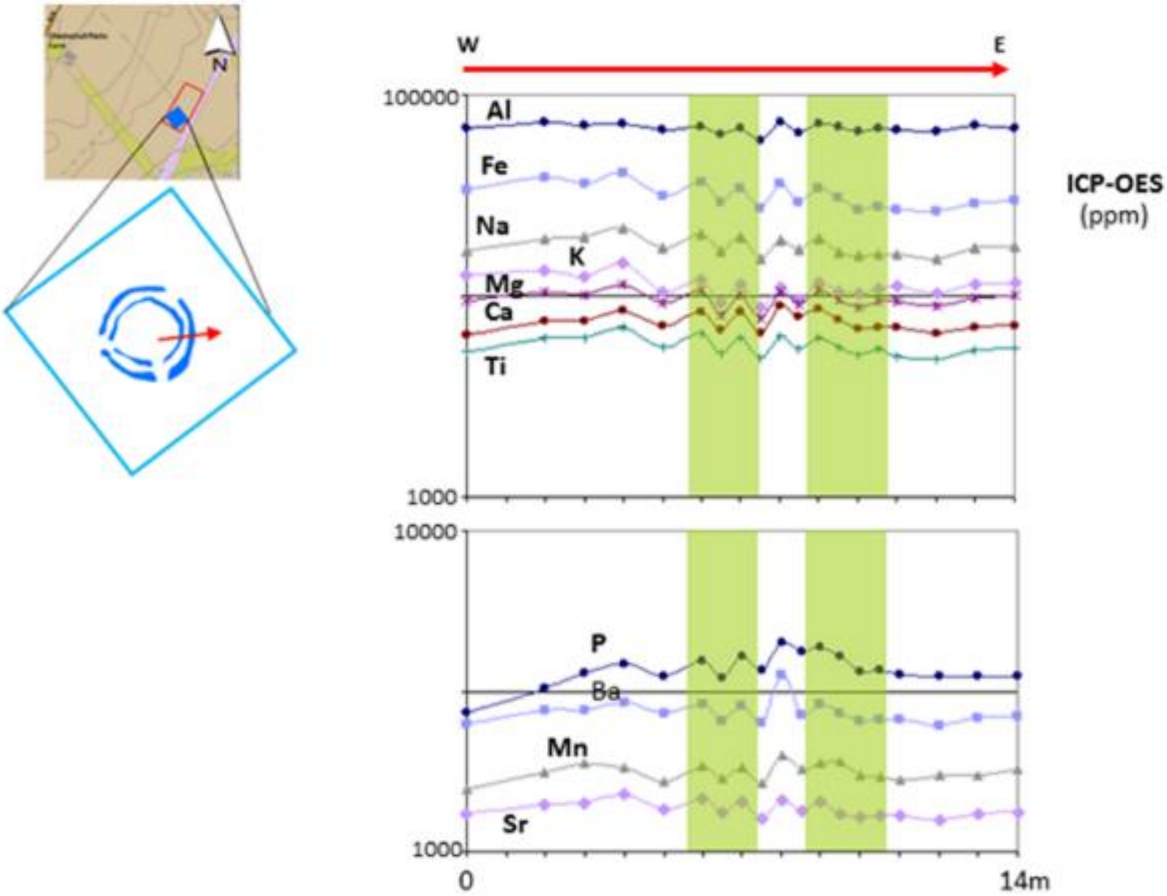

Figure 8: Topsoil sampling and ICP-OES results of a sampling line collected over the ditched enclosure 1 (Figure 7) at Chesterhall Parks Farm. The coloured bars mark the location of the ditches detected with the gradiometer survey.

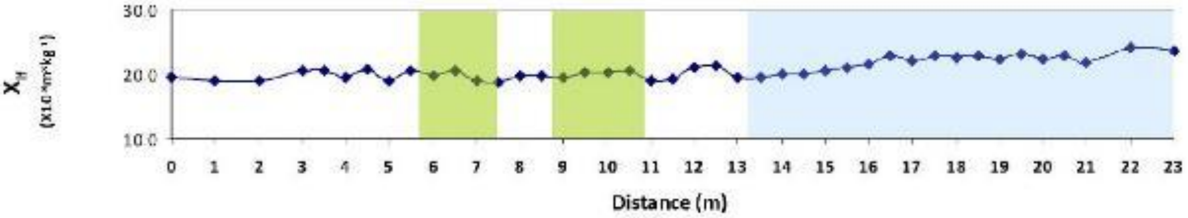

Figure 9: Surface distribution of magnetic susceptibility (χ_{lf}) of the soil samples collected at Chesterhall Parks Farm. The mark indicates the location of the ditch anomalies relating enclosure 1 (in green) and enclosure 2 (in blue).

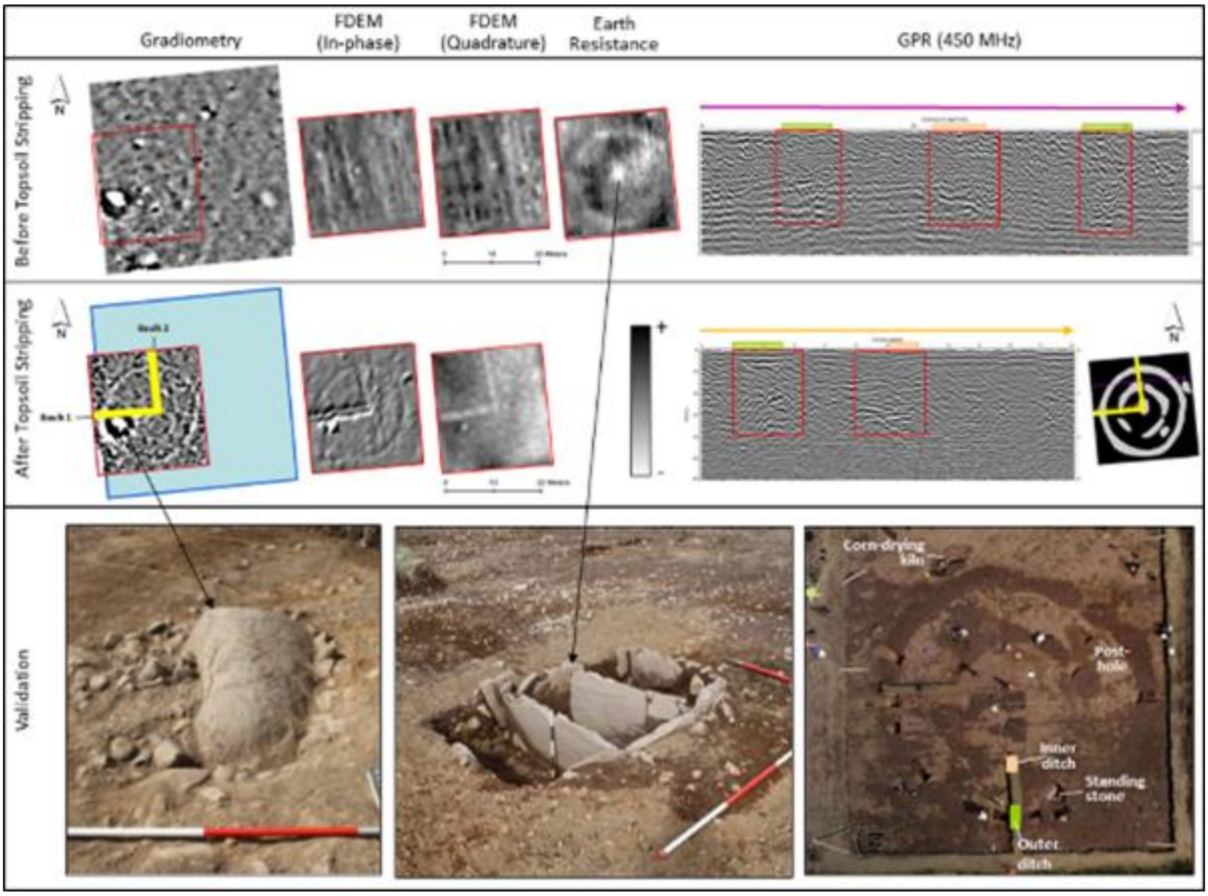

Figure 10: Results of the multi-technique geophysical survey (before and after topsoil stripping) and related archaeological features confirmed during the excavation at Forteviot. Following topsoil stripping, the exposed ditch deposits were mapped using a differential GPS, and their locations are indicated in the GPR reflection profiles and aerial photograph with the coloured bars. The gradiometer data were plotted at 10 (black)/-10 (white) nT. The FDEM (quadrature) plots show higher and lower values (mS/m) in black and white, respectively. High and low amplitudes in the GPR reflection profiles are shaded in black and white, respectively.

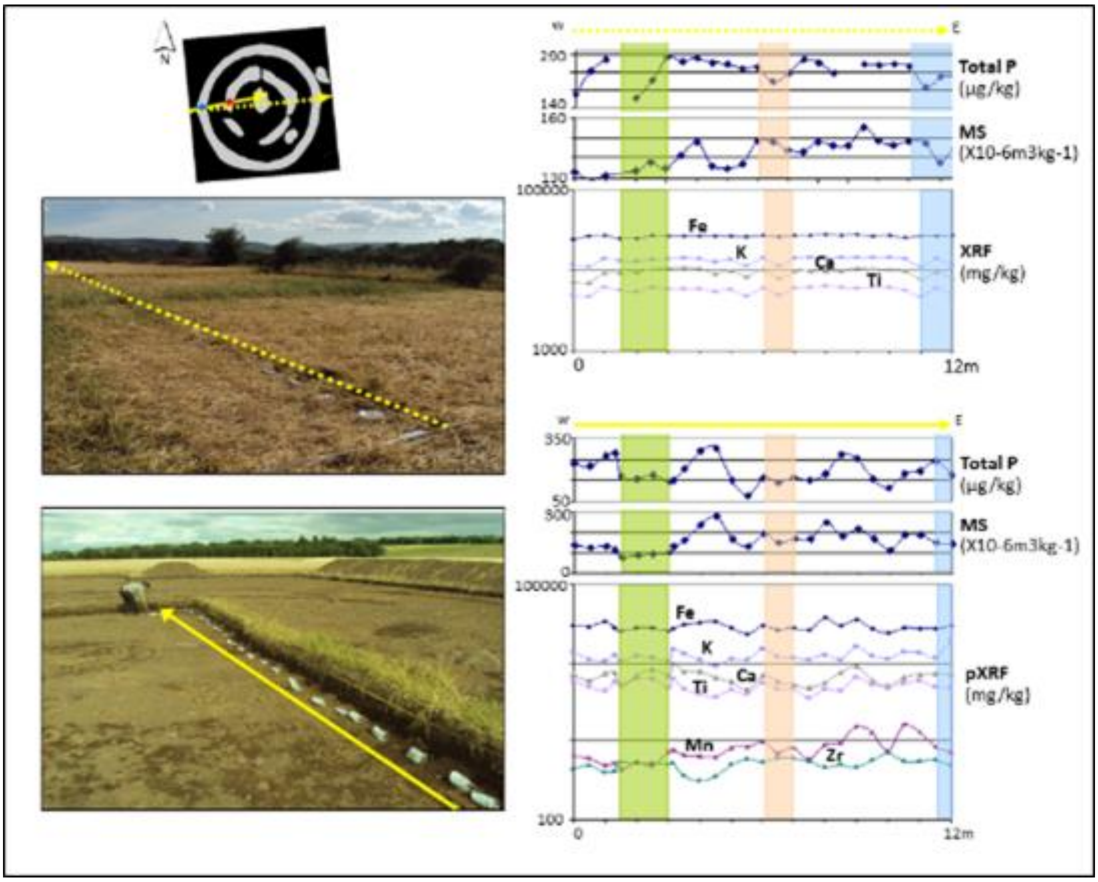

Figure 11: Topsoil sampling and selected results of the W-E sampling lines collected over the ditched enclosure at Forteviot before and after topsoil stripping (dotted and solid yellow arrows). The coloured bars mark the location of the outer (left) and inner (central) ditches and the triple cist burial (right).

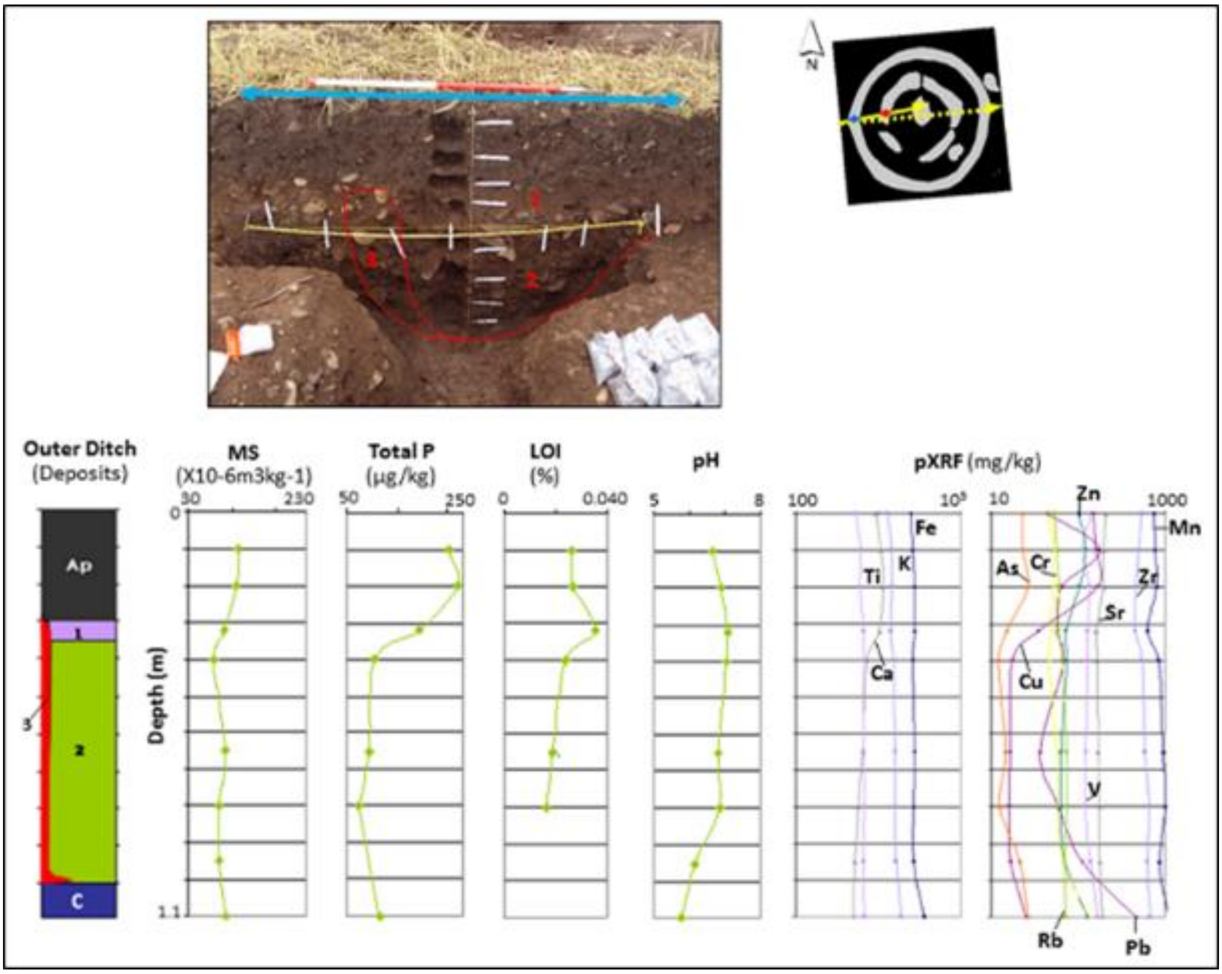

Figure 12: Selected results of the soil analyses of the samples collected from the exposed north facing section (blue double arrow) of the outer ditch at Forteviot.