Geoarchaeological Approaches to Pictish Settlement Sites: Assessing Heritage at Risk

Vanessa Reid

Due to the poor preservation of Pictish period buildings and the occupation deposits within them, very little is known of daily life in early medieval Scotland. In lowland and coastal areas, Pictish buildings are generally truncated by deep ploughing, coastal erosion, or urban development, while those uncovered in upland areas seem to have no preserved floor deposits for reasons that remain poorly understood. Geoarchaeological techniques are particularly effective in clarifying site formation processes and understanding post-depositional transformations. They are also a powerful research tool for identifying floor deposits, distinguishing their composition, and linking this to daily activities. However, archaeologists are often reluctant to apply geoarchaeological methods if they suspect preservation is poor or stratigraphy is not visible in the field.

This study therefore employs an innovative suite of geoarchaeological techniques to evaluate the preservation of Pictish period buildings and the potential that fragmentary buildings have to reconstruct daily life in early medieval Scotland. Alongside literature analysis and a desk-based comparison with national soil datasets, over 400 sediment samples from three key settlement sites were subjected to integrated soil micromorphology, x-ray fluorescence, magnetic susceptibility, loss-on-ignition, pH, electrical conductivity and microrefuse analysis. The combined data were successful in generating new information about the depositional and post-depositional history of the sites, preservation conditions of the occupation deposits, and activity areas within domestic dwellings. Most significantly, the integrated approach demonstrated that ephemeral and fragmented occupation surfaces retain surviving characteristics of the use of space, even if floors are not preserved well enough to be clearly defined in the field or in thin-section. A partnership with Historic Environment Scotland has channelled this work into research-led guidelines aimed at communicating geoarchaeological methods and principles to a wider audience.

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"The world of archaeology is so immense that a few feet from our chosen fairway we all stray into the rough grass of ignorance."

Martin Carver 2016: 17

"…every archaeological problem starts as a problem in geoarchaeology."

Colin Renfrew 1976: 2

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Copyright Statement

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1. Introduction

1.1. Overview

In Scottish history, there is perhaps no group that piques the curiosity more than the Picts. First mentioned by classical authors in AD 297 as a collective name for the more 'barbaric' people living north of the Roman frontier, the Picts became a political and cultural force in Scotland until the late first millennium AD (Evans 2019). As with most early medieval peoples of Britain, written evidence of their activity is limited and fragmentary, and archaeology has proved fundamental in bringing aspects of their society to light. Their impact is attested to through enigmatic carved stone monuments (Henderson and Henderson 2004; Noble et al. 2019a), new burial traditions (Maldonado 2011, 2013; Mitchell and Noble 2019), more developed systems of rulership and social structure (Evans 2019), and the re-emergence of fortified settlement (Alcock 2003: 179–199; Noble 2019a). However, it is the buildings and domestic dwellings – structures used for cooking, craftwork and resting – that capture the everyday lives of these people and connect us more meaningfully to their past.

In comparison with fortifications and high-status sites, the structures in which Pictish people worked and resided have received very little attention and there is currently a huge gap in our understanding of daily life in early medieval Scotland (also known as the 'Pictish period'). The key issue has been the very poor preservation of buildings, particularly across eastern lowland areas, which produce few artefacts and lack coherent occupation deposits (Hall and Price 2012). In many cases, the mechanisms behind this absence of detail are not fully understood and there has been little attempt to delve any deeper into the contributing factors.

This research aims to address these knowledge gaps by characterising the major post-depositional processes affecting Pictish settlement sites in eastern Scotland. It also explores the potential of integrated geoarchaeological analysis as a tool for clarifying these processes and identifying floor deposits, distinguishing their composition, and linking this to daily activities, floor maintenance practices, and living conditions. It utilises a research framework that has proven to be highly effective on historic, ethnographic and archaeological sites (Milek 2006, 2012a; Wilson et al. 2009; Jones et al. 2010; Milek and Roberts 2013; Borderie et al. 2020) as well as Pictish period deposits in the Western Isles (Sharples 2012) but has yet to be applied to dwellings in eastern Pictland. This chapter will introduce the research by first discussing the need for dedicated studies of Pictish settlement structures and their preservation, followed by the research aims and objectives, the limitations of the research, and finally the structure of the resulting thesis.

1.2. Research rationale

This thesis is concerned with Pictish settlement and structures in eastern Scotland, an area that for the purpose of this study principally lies between the Moray Firth in the north and the Firth of Forth in the south. Over the last few decades, our understanding of the area's settlement record has increased dramatically. New analysis of historical evidence has reconfigured the geopolitical landscape, moving the core Pictish kingdom of Fortriu from central Scotland to the shores of the Moray Firth (Woolf 2006). Aerial photography and topographic surveys have populated the landscape with new sites (e.g. RCAHMS 1990, 2007), and an accompanying explosion of archaeological excavations have resulted in new discoveries and the publication of key texts that specifically focus on the Pictish record of the area (see Noble and Evans 2019; Strachan et al. 2019). Research is fast-paced and thriving and there is a fantastic opportunity to meaningfully contribute to new and developing narratives.

However, there are several issues facing this flurry of archaeological activity. The number of known Pictish settlements is slight in comparison with neighbouring areas, such as early medieval England or Ireland, where thousands of sites have been recorded (Hamerow 2012; O'Sullivan et al. 2013; Carver 2019). Unenclosed settlements and structures in general have proven particularly elusive, meaning that trends and relationships between site types are difficult to determine and our understanding of the broader economic, social and political spheres in which these sites operated is still very limited. Intact floor deposits are rarer still, and detail regarding the organisation of domestic or industrial spaces, human-animal relations, floor maintenance practices and duration of use, and the scale or number of occupation events in individual sites and buildings is almost non-existent (Ralston 1997; Noble et al. 2020: 320). There is also concern over the extent to which the missing evidence has been hidden, truncated or completely destroyed, and the risk that the few known sites currently face. Though these issues are widely acknowledged, dedicated site-based characterisations or broader assessments of the impact of factors affecting preservation have yet to be undertaken on the Pictish settlement record. Interpretations are often based on an absence of evidence and rely on assumptions about the preservation environment rather than direct assessment (Ralston 1997; Noble et al. 2019b, 2020; Prado and Noble 2022). Combined, these issues have resulted in a relative dearth of research into daily life, and significant aspects of the settlement record, in particular domestic dwellings and unenclosed sites, continue to be left out of important syntheses (e.g. Blackwell 2019; Noble and Evans 2019).

The issues facing Pictish settlement studies can therefore be grouped into two categories – issues of preservation and survival, and issues of methodological approach. Whilst little can be done to address the lack of architectural detail, stratigraphy, or artefacts encountered during excavation, understanding *why* these occur is fundamental to creating reliable interpretations of the evidence. Poor preservation is indicative not only of methods of construction, abandonment, or use, but also destructive post-depositional events and diagenetic processes in the burial environment (collectively known as 'site formation processes' – see Schiffer 1983, 1985, 1987). Though we continue to discover an increasing number of sites, our understanding of them has stalled, and it is clear we can no longer rely on assumptions based on an absence of evidence. There is a desperate need for broad characterisations of preservation conditions, as well as detailed investigations at the site-level, to develop a foundational understanding of patterns in the distribution, scale and severity of post-depositional processes. Such assessments will be critical in ensuring that the limited cultural resource is managed effectively, and that sites most at risk of destruction (or those that currently have the best examples of preservation) are prioritised for excavation. This thesis first addresses these issues at a regional scale through a paper published in the journal *Heritage*. This presents a semi-quantitative literature analysis of preservation factors encountered across eastern Pictish settlement and explores whether it is possible to predict preservation conditions on these sites using established datasets on land use and soil conditions, without the need for intrusive investigation (Chapter 4 – Reid and Milek 2021). A second paper published in the journal *Medieval Settlement Research* builds on these results and evaluates the potential impact of preservation factors on our interpretation of the record (Chapter 5 – Reid 2021). Together, these review papers assess the threats that these sites face, both now and in the future, and offer guidance for future investigation.

With regards to the methodological issues, it has become clear that the thin, fragmentary, and seemingly homogenous nature of Pictish floor deposits has precluded their consideration as cultural artefacts. Despite widespread acceptance that floor deposits are a palimpsest and the product of hundreds of depositional events (see LaMotta and Schiffer 1999), the lack of discernible stratigraphic sequences has made it difficult to ascertain function and duration of use, and their assessment is often limited to basic field descriptions. Floor deposits are frequently treated as a single context and the biographies of Pictish structures remains a clear gap in our knowledge. The ability to assess these floors at a higher resolution – both spatially and in profile – could therefore improve our understanding of activity areas and the use of space, whilst adding considerable detail to assessments of the post-depositional processes affecting poorly preserved sites.

Geoarchaeology is a multi-disciplinary area of research that employs the techniques and principles of geology, geomorphology and soil science to understand and interpret the archaeological record (Davidson and Shackley 1976; Goldberg and Macphail 2006; Rapp and Hill 2006; Karkanas and Goldberg 2019). Whilst scales of analysis vary, most geoarchaeological investigations are concerned with understanding how deposits were initially laid down and modified through time. By forcing a consideration of the processes that form the archaeological record, it permits a fundamental differentiation between 'authentic' archaeological material, exogenous material, material which may be missing, and that which was never originally present (Weiner 2010: 46). Thus, by understanding the sedimentary context in which cultural remains are situated, it is possible not only to assess activity at the time of occupation but also the nature and integrity of the data that remains.

Numerous studies have demonstrated the value of integrating geoarchaeological techniques when examining structures and their deposits (Smith 1996; Entwistle et al. 2000a, 2000b, 2007; Shahack-Gross et al. 2005; Jones et al. 2010; Milek and Roberts 2013; Shillito et al. 2014; Borderie et al. 2020; Robertson and Roy 2021). They most commonly combine micromorphological, geochemical and sedimentological analyses, but can also involve microartefacts, plant phytoliths, and biomolecules. Specific case studies and their influence on the methodological framework of this project are discussed in Chapter 3. To build on this research and test the application of geoarchaeological methods to the Pictish settlement record, this thesis applies spatial geochemical and magnetic sampling (for pH, electrical conductivity, magnetic susceptibility, organic matter content and multi-element analysis) with micromorphological analysis from structures at three key settlement sites in eastern Scotland. They include a Pictish farmhouse in upland Perthshire, and two structures of unknown function in the coastal promontory sites of Burghead (Moray) and Dunnicaer (Aberdeenshire). Each site has a unique environmental setting that allows potential reasons for the fragmented settlement record to be assessed. This includes preservation conditions and post-depositional events, as well as the ways in which architecture and settlement location may have influenced archaeological signatures. This research also explores how the geoarchaeological data relates to evidence for internal activity and whether such integrated approaches may help interpret occupation activity in similar structures. These are the first dedicated geoarchaeological investigations of Pictish structures in eastern Scotland and thus have enormous potential to contribute new information about the daily life of early medieval society. As the majority of geoarchaeological studies conducted elsewhere have previously concentrated on well-preserved, historic, or ethnographic structures, these investigations will also test the techniques on archaeological sites with varying degrees of poor preservation.

1.3. Research aims and questions

The primary aim of this thesis is to identify the site formation processes which created, modified, and continue to affect Pictish sites in eastern Scotland. The secondary aim is to assess the value of integrated geoarchaeology for informing their research agendas and cultural heritage management solutions. To achieve this, the project has several research questions which require addressing. These have been divided into archaeological and methodological questions:

Archaeological questions:

i. What are the major post-depositional processes affecting the Pictish settlement record in eastern Scotland and how do these differ across a range of environmental settings?

ii. What are the major risks to Pictish settlement sites now and in the future?

iii. To what extent have major preservation factors influenced our interpretation of the Pictish settlement record?

iv. Do poorly preserved structures and occupation surfaces retain information relating to site formation and the use of space?

v. If information about site formation and the use of space can be found in occupation surfaces, what significance does this have for the interpretation of early medieval life and society?

Methodological questions:

vi. To what extent can national datasets on land use, soil conditions and erosion modelling be used to provide remote localised information on the preservation environment and predict post-depositional events and prospective threats to a region's archaeological resource?

vii. What is the most suitable suite of geoarchaeological and statistical techniques for investigating fragmentary buildings and occupation surfaces?

viii. What types of cultural heritage management issues can be addressed through geoarchaeological methods?

ix. How can geoarchaeological investigations be implemented more widely in Scottish archaeology?

1.4. Limitations

Despite our best efforts, no piece of research is ever perfect. With regards to the desk-based assessment of post-depositional processes affecting eastern Pictish settlement sites, this study is not exhaustive. Restrictions on the availability of grey literature, and a relatively small number of identified Pictish settlement sites, means crucial examples of localised preservation impacts are likely to be missing. Similarly, the factors mentioned in this study are not the exclusive determinants of the destruction or survival of archaeological material. Their inclusion is based on what has been identified during archaeological enquiry, which is the product of several methodological biases that include the scale and nature of an investigation, the experience and training of the excavator, and the techniques of analysis used. There is also an overwhelming bias in favour of modern rural settings, as almost no early medieval structural evidence has been found in urban contexts. Burghead is perhaps the closest example, with extensive remodelling during the construction of a nineteenth century town, however it is not a suitable analogue for cities or more populous settings. As such, the impact of urban development on the survival of the Pictish record almost certainly merits further consideration but is outwith the scope of this research.

Where possible, the sampling strategies for geochemical and micromorphological analysis were developed and executed by the author, in partnership with site directors and a highly experienced geoarchaeologist (Professor Karen Milek, primary supervisor to this thesis). This is the ideal scenario for subsequent analysis and interpretation, as it provides an intimate understanding of the site and an awareness of any issues which may affect sample integrity. This approach was successfully executed at the study sites of both Lair and Dunnicaer. Due to the author's unavailability, the sampling at Burghead was conducted by Óskar Sveinbjarnarson, a skilled excavator from the University of Aberdeen's Archaeology Department, in consultation with Professor Milek. Contact with Mr Sveinbjarnarson has been maintained throughout the project, and he has provided invaluable information regarding the site's excavation and sampling procedure.

Issues with sample and archive accessibility have influenced the nature of the research into the upland Perthshire farmhouse. At the outset of the project, it was intended to compare the micromorphological samples taken at Lair (Building 3) with those from an additional structure in the settlement (recovered in 2012 by a staff member at the University of Stirling). This would have permitted a direct comparison of preservation conditions and whether any differences related to dwelling activities could be discerned through micromorphology. Whilst this approach formed the basis of the research proposal and was agreed upon by the involved party prior to commencing the project, the archive material was never transferred and information regarding sample location remains missing. The thin-section laboratory at the University of Stirling closed in 2022 and the impregnated blocks have been passed to the author of this thesis in the hope that the archive material will resurface.

Finally, this thesis was largely developed during the COVID-19 pandemic and its impact on the project (and the author) has been undeniable. The original research plan proposed to open old excavation trenches in structures at the Pictish site of Pitcarmick (Carver et al. 2012) in order to take micromorphology samples from floor deposits and turf walls. The intention was to provide comparative data for Lair, offer new data on the formation processes affecting Pictish dwellings, and establish whether any changes in the preservation of the buildings following their re-burial could be observed. Scheduled Monument Consent was successfully obtained, however government-enforced limitations on travel, close working and the heather burning season (required to access the structures) meant that the timeframe was no longer feasible. Descriptions of the proposed works have been provided in Appendix 4.

1.5. Structure of the thesis

This chapter has provided an overview of the planned research and the need for dedicated studies of Pictish settlement structures and their preservation, including specific research aims and how they are to be approached. Chapter 2 focuses on the research context of this thesis, assessing the previous study of early medieval settlement in eastern Scotland, including structural evidence, methods of archaeological investigation, and theoretical and methodological issues. Chapter 3 concentrates on methodologies, beginning with a review of the geoarchaeological studies that have contributed to the methodological framework of this research, before covering the methods used, including on-site sampling techniques, laboratory processing and microscopy procedures.

The core of this thesis is composed of four research papers and a research-led geoarchaeological guidance document, each of which has been published or is soon to be published (Table 1.1). Each one is preceded by an introduction describing how the approach was formulated, how it relates to the overall aims of the research, and the methodologies used. Where these chapters include multi-authored papers, the student's and co-authors' contributions have been made explicit. Chapter 9, an integrated discussion chapter, brings together the results of these papers and considers the contributions that geoarchaeology has made to the interpretations of Pictish settlement structures and daily life in early medieval Scotland. It also evaluates the most suitable suite of geoarchaeological techniques for the analysis of fragmentary buildings and examines the greatest risks facing their cultural heritage management. This thesis concludes with suggestions for future research and a consolidated bibliography. Supporting data, including geochemical results, micromorphological datasheets, and details of the quantitative analyses, are provided in the Appendices.

Table 1.1. Summary of publications

Chapter	**Paper**	**Approach**
4	Risk and resources: an evaluation of the ability of national soil datasets to predict post-depositional processes in archaeological sites and heritage at risk	Literature analysis of post-depositional processes affecting early medieval Scottish sites and desk-based comparison with national datasets
5	A process of elimination? Reviewing the fragmented settlement record of eastern Pictland and its implications for future research	Literature review of post-depositional impacts and their influence on interpretations of the Pictish settlement record
6	Revealing the invisible floor: Integrated geoarchaeological analyses of ephemeral occupation surfaces at an early medieval farmhouse in upland Perthshire, Scotland	Integrated geoarchaeological study of an upland Pictish farmhouse lacking visible occupation surfaces
7	The role of geoarchaeology in the interpretation of fragmented buildings and occupation surfaces: The case of coastal settlements in northeast Scotland	Integrated geoarchaeological study of structures in two coastal promontory forts with fragmentary occupation surfaces
8	Geoarchaeology: A Short Guide (in partnership with Historic Environment Scotland)	Research-led practical guidelines supported by short case studies for the application of geoarchaeological methods and principles (aimed at a non-specialist audience)

2. Pictish Settlement in Eastern Scotland

2.1. The Picts – an overview

The Picts were an indigenous people of Scotland, who emerged during late Roman rule in the first millennium AD. Historical evidence of their presence is first recorded by classical authors in AD 297, where they are referred to as *Picti* – commonly translated as 'the painted ones' (Nixon and Rodgers 1994: 126; Foster 2014: 2). Fraser (2009: 37; 2011) has proposed the increasingly popular view that this term was coined by the Romans to refer to the more 'barbaric' people living north of the Roman frontier but was only employed by the Picts in the late seventh century following the establishment of the overkingship of Fortriu (Woolf 2006; Evans 2019: 17–18). The Pictish kingdom extended across the areas north of the Firth of Forth in central Scotland, right through the north-east, up to Sutherland and Caithness on the northern mainland, and into the Northern and Western Isles beyond (Noble 2019b: Fig. 2.1). The term 'Pictland' is a modern construct that has been widely adopted across the literature to refer to the areas in which Pictish activity and influence spread (Foster 2014: xxiv).

The lack of detailed historical references to the Picts has been a much-lamented aspect of their study. Glimmers of insight have been gained from Roman, Irish, and English texts, however there are few native records or historical accounts that pre-date the twelfth century (Ralston and Armit 2003; Noble et al. 2013; 1136–1137; Foster 2014: 13–21; Evans 2019). In their absence, Pictish activity has been attested to through material culture and changes in the political and architectural traditions of Scotland. Carved stone monuments known as 'symbol stones' are found in almost all corners of Pictland and have provided the most tangible, if inscrutable, evidence of Pictish presence (Henderson and Henderson 2004; Clarke 2007; Noble et al. 2019a). The emergence of formal cemeteries, including square and circular barrow monuments, are seen to have transformed the funerary landscape and indicate the emergence of new hierarchies in the post-Roman centuries (Maldonado 2011, 2013; Mitchell and Noble 2017). Accompanying these changes was the creation of more developed systems of rulership and social structure (Evans 2019) and the re-emergence of fortified settlement (Alcock 2003: 179–

199; Noble 2019a). The adoption of Christianity also took place within this period and is evidenced by the inclusion of Christian imagery on symbol stones and the establishment of iconic monastic sites such as Portmahomack (Carver 2016; Evans and Noble 2019). This activity continued until the end of the first millennium AD, when the Picts merged with the Dál Riata – Gaelic speakers who lived in the part of western Scotland that comprises the areas of modern day Argyll and Bute (Foster 2014: xxiv). The kingdom of Alba was firmly established by the end of the tenth century, and the Pictish language, culture and identity became lost or assimilated (Evans 2019). The Picts are thus considered the last major ethnic identity in the British Isles to become extinct (Evans 2019: 10).

2.2. Eastern Scotland

This thesis focuses on evidence of Pictish settlement within an area of eastern Scotland that principally lies between the Moray Firth in the north and the Firth of Forth in the south. Sites are primarily concentrated within the modern council areas of Moray, Aberdeenshire, Angus, and Perth and Kinross, however several lie slightly further south in Fife or north in Easter Ross. Throughout the thesis, this area is referred to by the terms 'eastern Scotland' or 'eastern Pictland' (Fig. 2.1).

Eastern Scotland comprises a wide range of different geological, topographic and environmental settings. The Highland Boundary Fault, which traverses the Scottish mainland, separates the area into two distinct geographic regions; the Highlands in the north and west, and the Lowlands in the south and east (McKirdy et al. 2017). Aberdeenshire and Moray lie north of the Mounth mountain barrier, whilst the eastern lowlands of Angus and Perthshire lie to the south; the Grampian Mountains occupy the majority of the western and central zones of the area (Fraser and Halliday 2011: 307; Fig. 2.1). The underlying geology of the area is varied; Moray is predominantly covered with Old Red Sandstone, Aberdeenshire and the Grampian Mountains are littered with granite intrusions, whilst the Midland Valley (containing Perthshire, Angus and Fife) has relatively young rock formations, mainly sandstones or mudstones, with basaltic rocks in the east (Browne et al. 2001; Merritt and Leslie 2009; Auton et al. 2011). Bedrock is predominantly overlain by deposits of glacially transported material, consisting of a heterogenous mixture of silt, sand and gravel (BGS 2022). This diversity in geologic structure and topography has resulted in a variety of soil types and environmental settings. Acidic podzols are the most common soil type encountered and are present across all topographic areas and at all elevations. Fertile brown earths are more restricted to the warmer, drier climates of lowland areas but can also occur in sheltered highland areas and on base-rich parent material, whilst organic peat soils and blanket peat are primarily restricted to upland locations (James Hutton Institute 2022).

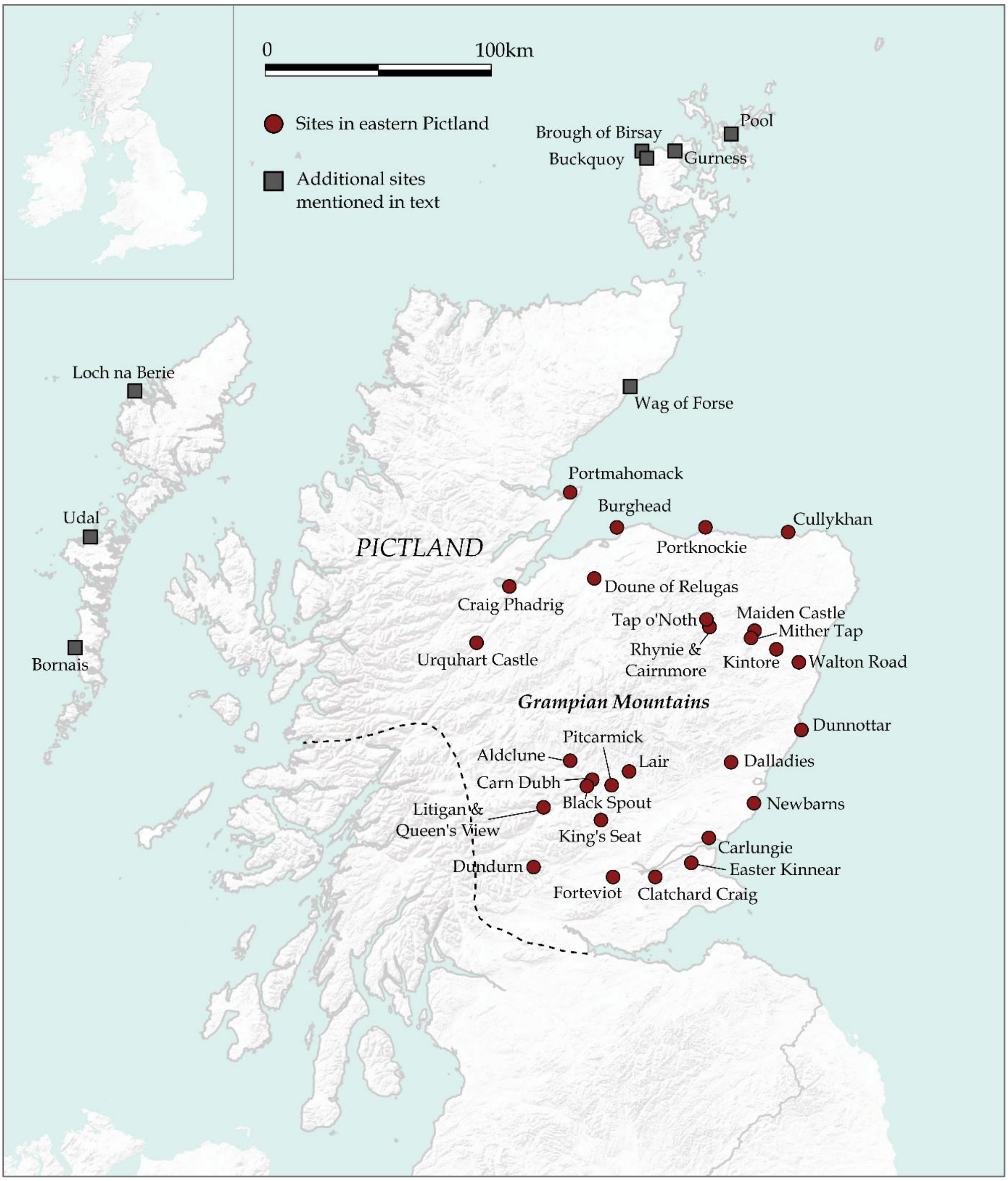

Fig. 2.1. Scotland showing extent of Pictland (north of dotted line, including Western and Northern Isles) with sites referenced in Chapter 2

The climate of eastern Scotland is defined by cool summers and mild winters; mean annual temperatures over the region vary from about 9°C around the Firth of Forth to less than 6°C over the higher ground of the Grampian Mountains (Met Office 2016). Rainfall also varies; areas in Fife and the Moray Firth receive less than 700 mm of rainfall in an average year, whereas the southern Grampians receive over 1500 mm (Met Office 2016). As with the rest of the world, Scotland has already witnessed a considerable shift in these patterns as a result of climate change. The average temperature in the last decade has increased by around 0.7°C, and rainfall has increased by 9% (Adaptation Scotland 2021). The overall trend is now towards hotter, drier summers and warmer, wetter winters with more extreme weather events. Scotland is known to have witnessed two major episodes of climatic change during the middle of the first millennium AD – the Early Historic Cold Period from AD 400–600 and a gradual warming after AD 600 that culminated in the Medieval Warm Period AD 950–1250 (Tipping 2008; Ross 2011: 9; Cook 2015: 15).

Early medieval settlement and land use strategies appear inherently linked with eastern Scotland's topography, soil, and climate, and were at least partially conditioned by the related availability of building materials (see Ralston 1997; Hooper 2002; Edwards and Ralston 2003; Strachan et al. 2019: 132–146). Pollen records for upland Perthshire indicate that timber availability was limited during the Pictish period. Substantive woodland loss of birch, hazel and oak is estimated to have begun c. 700 BC and though there is evidence for recovery after c. AD 150, additional felling pushed eroded soil across the peat c. AD 300 and a final reduction is directly dated to AD 630–840 (Tipping 1995a, 2013). Heath and grassland became the dominate land cover in these areas, resulting in the availability of turf for construction (Strachan et al. 2019: 119). The narrative is similar for lowland areas, where there appears to have been major deforestation in favour of cereal cultivation and pastoral farming (Tipping 1995b; Strachan et al. 2019: 12–13; Jones et al. 2021), though hardwoods for building would have still been available (Ralston 1997: 19; see Noble et al. 2019b). These materials are a marked contrast to Pictish period structures across the far north and west, including Orkney, Shetland, and the Western Isles, which were primarily constructed in stone (Ralston 1997; Geddes 2006). Today, land use practices are differentiated across the regions; hill sheep farming dominates the upland environments, whilst arable field crops are concentrated in the lowlands (NatureScot 2020). The resulting suite of environmental settings have not only influenced the location and construction of Pictish settlement, but also played a major role in its survival, identification, and study.

2.3. History of research

Archaeological interest in the settlement of the eastern Picts can be traced back to the eighteenth and nineteenth centuries, with the antiquarian excavation and survey of upstanding fortified sites such as Dundurn and Burghead (Roy 1793; MacDonald 1862; Young 1890, 1891, 1893; Christison 1898). This period also marked the discovery of some the most impressive pieces of Pictish material culture, such as the Gaulcross hoard in Aberdeenshire, and developed the classification of the carved stone record that became symbolic of Pictish presence and identity (Stuart 1867; Anderson 1881; Allen and Anderson 1903; see Noble et al. 2019a). These elements of material culture were critical in defining, with some precision, the boundaries of Pictland and indicating cultural unity across its reach. The majority of historic and linguistic scholarship during this era was concerned with clarifying Pictish lineage, language, politics and origins, and chartered the course for supporting archaeological agendas (Chalmers 1807).

Questions of origin persisted well into the twentieth century but were plagued by the inability to define any single fortification, dwelling or burial as Pictish. The seminal edited volume *The Problem of the Picts* (Wainwright 1955a) captured the complexity of this discourse and addressed it with considerable intellectual agility, demonstrating the value of archaeology in a study area that had all been written off as impenetrable (Driscoll 2011: 245). With regards to settlement evidence, the primary concern of this thesis, the most notable contribution was Feachem's (1955) analysis of fortifications, which built on Stevenson's (1949) definition of the 'nuclear' fort and drew attention to a group of small, circular fortified settlements he termed 'ringforts'. Wainwright's own chapter on houses and graves remained unable to determine any dwelling or burial as Pictish (reflecting a paucity of evidence for both) but suggested several categories of settlement where evidence may be found, including souterrains, fortifications, and the deserted remains of other periods (Wainwright 1955b). His contribution represented the first effort to engage in the domestic sphere and demonstrated the clear need for dedicated investigation of a Pictish house. It also highlighted the problems with developing such an approach; fortifications can dominate landscapes for centuries and graves are rarely repurposed, whereas houses tend to be pulled down and rebuilt, leaving fewer traces for the archaeologist (Wainwright 1955b: 88).

Other chapters in the volume wrangled with philological evidence of settlement geography, such as Jackson's distribution map of the prefix '*pit*' – a later form of *pett*, interpreted as meaning parcel of land or farmland (Jackson 1955: 146–148). The nomenclature was shown to exist almost exclusively on the eastern side of the country and was especially concentrated in Perthshire, Angus and Aberdeenshire, emphasising the idea that the northeast was the Pictish cultural heartland. It had long been recognised that modern farms which retained this place-name occurred on favourable agricultural land (e.g. Watson 1926: 407), and Jackson's work stimulated further research that now forms the basis of many modern understandings of Pictish settlement geography (e.g. Whittington and Soulsby 1968; Whittington 1975; Cottam and Small 1974). Recognition that the distribution of *pit* place names and symbol stones in this area was remarkably similar, with the majority occurring on well-drained soils below 183m OD, suggested that settlement sites were likely to be located at low altitude on good quality agricultural land, essentially providing a map of Pictish agrarian economy (Whittington and Soulsby 1968: 124; Whittington 1975: 102 – though this is not without considerable critique, see Shepherd 1983: 328–329; Halliday 2006; Fraser and Halliday 2007: 130–133, 2011: 310).

The Problem of the Picts thus formed the baseline for all subsequent archaeological investigation into Pictish settlement and domestic architecture. It was composed on the eve of the radiocarbon revolution – a development which threw prehistoric chronologies around the world into sharp relief. The ability to provide absolute dates and test historically-referenced sites should therefore have transformed the settlement record in eastern Scotland from the late 1960s, though this was only partly the case. In general, the limited historical sources proffered few place names or site locations from which successful archaeological investigations were launched. Leslie Alcock's long-term research programme into historically documented fortifications explored the majority of these references, with excavations at the royal palace of Forteviot (Perthshire) and Dunnottar Castle (Aberdeenshire) both failing to identify any early medieval deposits or defenses (Alcock and Alcock 1992). Structures were identified at Urquhart Castle (Inverness), however the lack of fortifications meant that the excavation was ultimately deemed unsuccessful (Alcock and Alcock 1992). Dundurn hillfort in Perthshire proved the lone exception in the area, revealing a complicated sequence spanning the sixth to ninth centuries AD that included a summit citadel and a series of lower enclosures (Alcock et al. 1989). More recent excavations at Forteviot have since encountered early medieval grave cuts, pits, postholes and structural beam slots, however the location of the sought-after high-status building or 'palacium' remains unresolved (Campbell and Driscoll 2020: 102).

By contrast, excavations based on archaeological evidence or conducted as rescue works, such as Craig Phadrig (Inverness – Small and Cottam 1972), Burghead (Moray – Small 1969; Edwards and Ralston 1978), Cullykhan (Aberdeenshire – Greig 1970, 1971), Portknockie (Moray – Ralston 1980; 1987) and Clatchard Craig (Fife – Close-Brooks 1986, 1987), returned a series of Pictish dates and quickly provided a corpus of fortified sites across the area. Yet, some of this work has never been fully published (e.g. Small and Cottam 1972 – see McCaig 2014), and the work was relatively piecemeal, resulting in poorly understood sites and several regional settlement surveys that contained very little detail (Shepherd 1983; Alcock 1984; Watkins 1984). However, their analysis did permit one significant theoretical development – a shift away from discussion of Pictish origins and towards description of their activities (Watkins 1984).

From this point we can see the development of a significant imbalance in Pictish settlement studies across eastern Scotland. In an area where for so long Pictish presence was deemed inscrutable, fortifications marked the natural target for research. They were, by character, more accessible; sites were often situated in prominent locations or had upstanding remains that could be identified on the ground or through aerial photography. Studies since the 1950s had already acknowledged at least three main types of defended settlement in eastern Pictland – summarised by Noble (2019a) as nuclear hillforts, ringforts/settlement enclosures, and coastal promontory forts – all of which provided an opportunity to test new theories regarding site typology and date. The different character of these settlements has been discussed in length elsewhere, however all were taken to indicate settlements of power and high or modest status (see Feacham 1955; Ralston 2004; Noble 2019a). On the other hand, rural settlement (deemed to relate to lower societal classes) remained elusive and understudied.

This was not the case across all of Scotland. In the Northern and Western Isles, unfortified settlement (including the reuse of complex Atlantic roundhouses) comprised the majority of evidence for early medieval activity (Ralston 1997: 22). Interest was stimulated by the excavation and prompt publication of Buckquoy in Orkney – a multi-cellular turf and dry-stone building that had been subjected to multiple rebuilding episodes (Ritchie 1977). Sites including the Brough of Birsay (Orkney – Ritchie 1986), Gurness (Orkney – Hedges 1987), Udal (North Uist – Crawford and Switsur 1977), Loch na Berie (Lewis – Harding and Armit 1990) and Pool (Sanday, Orkney – Hunter 1990) subsequently developed an impressive corpus of ground plans, almost all of which incorporated drystone masonry. Similar structures were identified on the northern mainland, at the Wag of Forse in Caithness, however the variety in architectural forms and surviving stone foundations seemed to have no direct parallels in the east (Ralston 1997: 30). Early medieval lake dwellings known as 'crannogs' were also not found in the east and appeared regionally restricted to west and southwestern Scotland (Clarke 2012: 89).

In the absence of diagnostic ground plans, efforts to identify rural settlement primarily concentrated on post-souterrain activity in Iron Age sites. Wainwright (1955b, 1963) and Watkins (1980a, 1980b, 1984) presented the majority of research in this area, suggesting a relationship between the prehistoric subterranean structures and early medieval activity (see Maxwell 1987 for a review). Primarily this related to later constructions (e.g. Carlungie in Angus) or carbonised remains (e.g. Dalladies, Aberdeenshire), and others have argued that the deliberate infilling of these structures indicated an effort to continue occupation within the area (e.g. Dunwell and Ralston 2008a: 135). However, no souterrains were accompanied by clear evidence of a Pictish period building and all appeared to have been abandoned by the third or fourth century AD (Wainwright 1955b; Watkins 1980a, 1980b, 1984; Driscoll 2011: 262). In the absence of more tangible evidence, research into post-souterrain activity dwindled towards the end of the twentieth century.

Evidence related to daily life and activities was also missing from fortified sites. This largely resulted from the academic discourse of the period, where archaeological research agendas continued to be driven by the questions asked of historical sources. Excavations – including Leslie Alcock's programme of work – prioritised the identification of sites referenced in siege accounts and concentrated on small-scale assessments of their fortifications rather than internal features (e.g. Small and Cottam 1972; Alcock 1989; Alcock and Alcock 1992). There was also an underlying reluctance to apply developing methods and new theories of social archaeology to the identification and study of Pictish settlement (see Watkins 1984). Preservation was another factor; the few structures that were encountered (e.g. at Portknockie and Clatchard Craig) were highly fragmented, offered little architectural detail, and provided no stratigraphic resolution from which to define phasing, status or function (Close-Brooks 1987: 29; Ralston 1987: 19). Low artefact recovery and poor floor preservation became characteristic features of individual Pictish structures and precluded the analysis of settlement at the basic level of the individual household (Watkins 1984: 65, 74). Thus daily life remained intangible and perpetuated a focus on high-status sites, fortifications, and political histories.

A remarkable acceleration in Pictish settlement studies was witnessed from the 1990s onwards. Academic interest was greatly invigorated by Alex Woolf's reassessment of the historic sources and relocation of the core Pictish kingdom of Fortriu from central Scotland to the shores of the Moray Firth (Woolf 2006). This coincided with the publication of fourteen seasons of excavation at Portmahomack in Easter Ross, whose 'strip-and-map' technique identified a Pictish monastery and secular settlement, and provided a welcome contrast to the key-hole strategies that had defined excavation tradition in the area (Carver 2008, 2016; Carver et al. 2016). These developments, coupled with catalogues of regional archaeology and new fort typologies (see RCAHMS 1990, 1994, 2007), prompted a wealth of new excavations conducted through long-term research projects such as *Strathearn Environs and Royal Forteviot* (Campbell and Driscoll 2020; SERF 2022), *The Hillforts of Strathdon* (Cook 2015) and the *Northern Picts* (see Noble and Evans 2019). Their combined results indicated that an increasingly diverse range of fortified architecture was associated with the developing systems of power and governance across eastern Pictland (Noble 2019a: 39). Of particular significance to this thesis, however, was the identification of 48 structures constituting a previously unrecognised form of unenclosed settlement in Perthshire – turf and stone longhouses with rounded ends known as 'Pitcarmick-type' buildings (RCAHMS 1990: 12–13). Their excavation provided the most tangible connection to lower societal classes and Pictish daily life, and fundamentally changed our understanding of rural settlement in early medieval Scotland (see Carver et al. 2012; Strachan et al. 2019; section 2.4.2 and Chapter 6 of this thesis).

The summary presented above provides an overview of the major developments in Pictish settlement studies across eastern Scotland. While not exhaustive, it is possible to identify several outstanding issues that continue to affect our understanding of the record. Even amongst the widely studied fortifications, fewer than ten hillforts in Pictland have been radiocarbon dated to the early medieval period – though more have been proposed through their morphology (Ralston 2004; Noble 2019a: 41). Similarly, few Pitcarmick-type structures have been dated, and only a handful of *pit* place-name sites have been ground-truthed through archaeological investigation; their distribution patterns therefore remain largely untested as indicators of broader settlement geography. Reconnaissance efforts that identified settlement in upland landscapes have also proven less successful in populating lowland settings. This has been interpreted as the result of destruction by later sites and agriculture (comparison of the RCAHMS surveys of north-east (1990) and south-east (1994) Perthshire illustrate this well – Strachan et al. 2022), or climatic conditions and freely-draining soils in northern areas that produce few detailed cropmarks from which to launch archaeological campaigns (RCAHMS 2007 – though see Noble et al. 2019b for the exception at Rhynie). Thus, there remains relatively little evidence for Pictish settlement in eastern Scotland in comparison to early medieval Britain and Ireland, where thousands of sites have been recorded (e.g. Hamerow 2012; O'Sullivan et al. 2013; Carver 2019).

Our understanding of rural settlement also remains far behind that of high-status sites. Though a focus on fortifications can be tracked throughout the research history, it was arguably exacerbated by the delayed dissemination of findings from the structures at Pitcarmick, which were not published until two decades after their excavation (excavated 1993–1995, published 2012; Carver et al. 2012). Detailed results were excluded from important syntheses – e.g. Ralston's (1997) chapter on 'Pictish homes' and Alcock's (2003) overview of building diversity in Britain – and it would be 25 years after their excavation that a comparative example would be published (see Strachan et al. 2019). The impact of this is perhaps best demonstrated by comparison with excavation traditions in the Northern and Western Isles, which were stimulated by the prompt publication of Buckquoy (Ralston 1997: 22). Furthermore, issues of preservation and poor floor survival have not been adequately addressed and continue to limit structural, social, and cultural interpretations across all manner of Pictish settlement (see Ralston 1997; Noble et al. 2020; Strachan et al. 2019). As a result, questions of daily life remain unresolved, and a focus on high-status sites and culture continues to dominate research agendas and national syntheses (e.g. Clarke et al. 2012; Blackwell 2019; Noble and Evans 2019).

Returning to *The Problem of the Picts*, it is clear that many of the narratives and conclusions in the volume have now been discredited or superseded by new evidence (see Driscoll et al. 2011). Yet *The Problem of the Picts* represents the very first interdisciplinary study of Pictish Scotland and kindled an archaeological interest in their culture, identity and settlement that persists to this day (Crawford 2011). One only needs to look at the series of related publications and anniversary conferences as testimony to its enduring value (Small 1987; Driscoll 2011 – see Driscoll et al. 2011). Nevertheless, the term 'problem' has been seen by some to have perpetuated the idea of a 'lost' people (Driscoll 2011: 245–246; see Carver 2011), and the prevailing narrative of eastern Scotland remains that of a *terra incognita* (Alcock 1988, 2003; Driscoll 2011; Fraser and Halliday 2011; Prado and Noble 2022 – though see Cook 2015). The following discussion illustrates in more detail the evidence base, particularly the structural evidence, from which many of our current conclusions of eastern Pictish settlement have been drawn and on which this thesis is largely grounded. It will discuss the physical characteristics of structures, general trends in the data, and methods with which these sites have been approached, before returning to the concept of a *terra incognita* and the extent to which this truly reflects the Pictish settlement record.

2.4. Settlement evidence

Settlement is a multi-faceted construct, which can denote any scale of residence from a single house to a large urban metropolis (Ulmschneider 2012). For the purpose of this study, settlement is simply defined as a place in which people lived and worked. Restrictions have not been placed on the size, number or type of structures which constitute a Pictish settlement, nor on what these might indicate in terms of the status, role, or relationship of the occupants (following Brück and Goodman 1999: 7). The truth is, we simply do not have enough information available to answer these questions.

2.4.1. Enclosed settlement

Within Scottish studies, settlement is broadly categorised into two group – *enclosed* (sites bounded by fortifications or enclosures) and *unenclosed* (structures and features outwith any formal enclosing elements) (e.g. Cook 2015). The former, which includes all types of fortified settlement (see Noble 2019a) alongside the recently discovered elite lowland power centre at Rhynie (Noble et al. 2019b) and the monastic site of Portmahomack (Carver 2016), has comprised the majority of research across the mainland but provided comparatively little evidence for daily life. It is outwith the scope of this review to provide a detailed account of each type of enclosed settlement – nor would this be relevant to the ensuing papers – however it is worth clarifying that the role of enclosed settlement in a military sense would have been limited. Historical records of early medieval warfare almost always convey that battles took place in the open, and other roles are therefore likely to have involved elite residency and the ideological dimensions of rulership and power (see Woolf 2007: 29–30; Dunwell and Ralston 2008: 80–83; Cook 2013; Noble 2019a: 50–57).

The scale and complexity of enclosed settlement have been taken as indicators of their high status and role in early medieval power dynamics (Noble 2019a). Significant labour forces and considerable quantities of natural resources would have been expended on enclosing works, particularly in the case of large constructions such as the defenses at Burghead promontory fort (Dunwell and Ralston 2008a: 77–78; O'Driscoll 2017). The frequent presence of Pictish sculpture, and evidence for non-ferrous metalwork production and distribution, further supports interpretations of high status and indicates that material culture was an important mechanism of power and wealth (see Noble et al. 2019b: 85–86). Notably, several settlements demonstrate the reuse and reoccupation of Iron Age sites during this period – for example Craig Phadrig hillfort (Inverness – Small and Cottam 1972; McCaig 2014; Peteranna and Birch 2019), Doune of Relugas hillfort (Moray – Noble 2019a: 46), and Cullykhan coastal promontory (Aberdeenshire – Greig 1970, 1971) – perhaps legitimising power through memory (Driscoll 1998; see Williams 2006; Semple 2013; Williams et al. 2015; Fentress 2018).

The construction and re-occupation of fortified settlement in Pictland resumed after a hiatus of approximately 400 years (Cook 2011a, 2013; Noble 2019a: 50). The multiple types of enclosed settlement (summarised by Noble 2019a) were in existence by the fifth and sixth centuries AD, making them part of a broader trend observed elsewhere in northern and western Britain and Ireland (Edwards 1990; Alcock 2003). More nuanced developments can also be observed; smaller ringfort settlements decreased from the seventh century onwards, and the focus of construction and use was directed towards larger and more complex sites such as Burghead (Noble 2019a: 50–51). Smaller enclosures may therefore have represented more localised power centres, which were superseded in response to the adoption of Christianity and/or the establishment of the overkingship of Fortriu (Noble et al. 2013: 1143). Certainly, the traditional narrative for the larger hillforts of Pictland and early medieval Britain is that they resulted from changes in political structure during the mid-first millennium AD (Noble 2019a: 51). However, there are considerable blank areas in the distribution of enclosed settlement across eastern Scotland, most notably in Angus and Perthshire, where even undated examples of hilltop fortifications are rare (Dunwell and Ralston 2008: 63; Strachan et al. 2019: 132). Ongoing work at King's Seat above Dunkeld has provided evidence for high-status metalworking (MacIver and Cook 2017, 2018, 2019), and historical references to the lowland site of Forteviot in the ninth century suggests that this settlement type was likely to have been important towards the end of the Pictish period (see Campbell and Driscoll 2020). However, the overall record cannot be compared with that of Moray and Aberdeenshire, and our understanding of enclosed settlement patterns is profoundly skewed towards the north.

For the few structures identified within enclosed settlement, the evidence is scant. A structure in Portknockie promontory fort, Moray, consisted of little more than single-course walling, however the presence of an internal post-pad with no associated postholes offered early evidence that buildings were constructed using non-earth-fast methods (Ralston 1997: 24; Fig. 2.2). It was also noted that whilst soil covering the site contained material culture, there was no discernable stratigraphy (Ralston 1987). This was similarly the case at Clatchard Craig hillfort, where only a shallow layer of soil lay above the bedrock and contained no clear occupation deposits (Close-Brooks 1987: 29). A well-built rectangular hearth indicated the presence of a structure, and it was surmised that this probably constituted a rectangular house, however no additional structural evidence was discovered and the site has now been completely destroyed by quarrying (Close-Brooks 1987: 29; Fig. 2.2).

Excavations of ringforts at Litigan and Queen's View (Taylor 1990), Aldclune (Hingley et al. 1997) and the Black Spout (Strachan 2013: 27), all Perthshire, revealed a broad – if tenuously dated – chronology of construction and re-occupation extending from the Late Iron Age to the end of the first millennium AD. Their internal diameter ranged between 15–30 m, with substantial stone walls up to 3 m thick and had either single or multiple hearths, the latter perhaps indicating a division of space (Taylor 1990: Figs. 2 and 3; Hingley 1997: 450). Taylor (1990) concluded that the enclosures were most likely roofed, resulting in their reinterpretation as 'homesteads' rather than ringforts – terminology that was later adopted by Hingley (1997: 447). However, finds were limited and no occupation deposits were identified in their interiors to further deduce function or the nature of early medieval occupation. It was suggested that heath or bracken may have been used as floor coverings in response to the uneven subsoil at Litigan but this was not substantiated through further analysis (Taylor 1990: 27). Maiden Castle ringfort in Aberdeenshire also revealed evidence of residency, although here two rectilinear structures were found within the inner enclosure, making it more likely that the enclosure itself was not roofed (Cook 2011b). This difference may be attributable to the fact that some of the Perthshire examples had clear Late Iron Age origins with Pictish reuse (Hingley 1997; Strachan 2013: 27, 55), whereas Maiden Castle was a *de novo* early medieval construction (Cook 2015: 28). This could suggest that the nature of occupation and status of the residents differed between these two examples, with the former perhaps being more opportunistic and lower in standing. Test pits outside Maiden Castle fort also identified cobbled surfaces, indicating that settlement activity (in this case non-ferrous metalworking) was not reserved to the fort interior (Cook

2011b). This has important implications for future excavations, which typically use enclosing features to confine archaeological investigations.

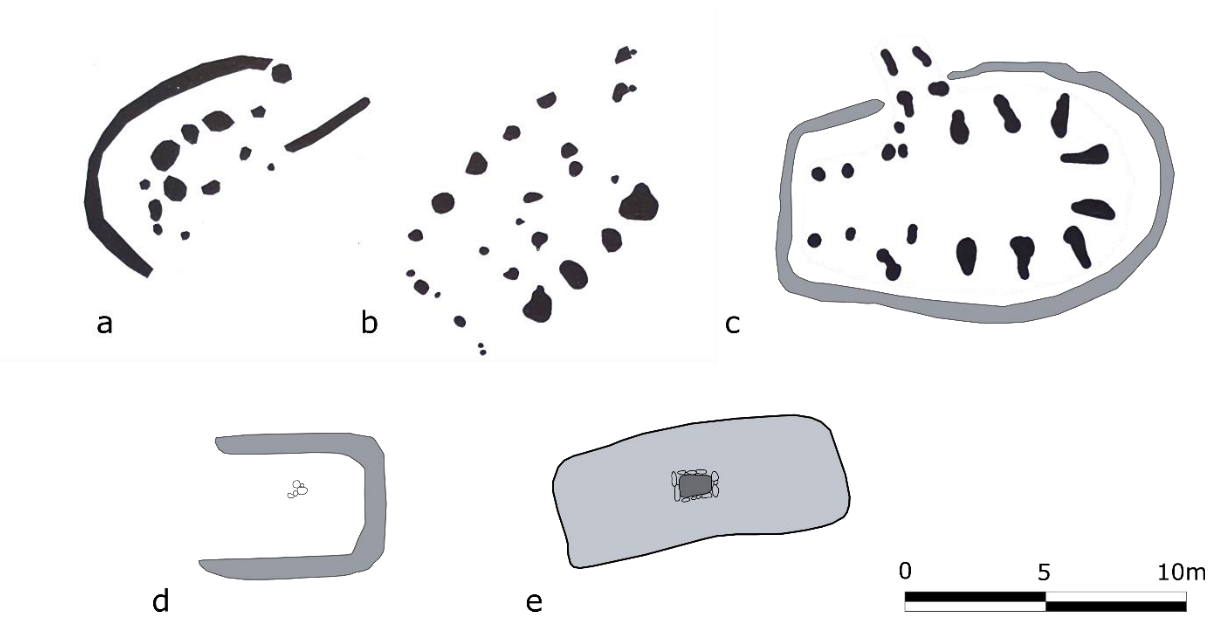

Fig. 2.2. Enclosed Pictish structure plans (after Noble and Evans 2022): (a) and (b) Rhynie, Aberdeenshire; (c) Portmahomack, Easter Ross; (d) Portknockie, Moray; (e) Clatchard Craig, Fife

Additional structures have been identified in the monastic site of Portmahomack. The most well-known of these is Structure 1, referred to as the 'bag-' or 'heel-shaped' building because of its appearance in plan (Carver 2016: 134; Carver et al. 2016: 228–246; Fig. 2.2). Evidence indicated the building had been constructed with a turf wall and stone or plank internal revetment and was interpreted as a craft workshop that had at least two phases of the use – the first during the eighth century and the second in the ninth to eleventh centuries, when it was converted into a grain drying kiln (Carver 2016: 133–138). Similar structures have also been uncovered at Rhynie (Noble et al. 2019b: 69–70) and Burghead (Gordon Noble pers. comm; see Chapter 7 of this thesis; Fig. 2.2). Of the three structures identified at Rhynie, all had truncated floor plans with very little internal detail, assumed to be the result of later cultivation that had removed structural features and floor layers (Noble et al. 2019b: 69–70). It was also assumed that their construction incorporated timber with few earth-fast elements and likely had turf or stone outer walls, however none of the structures were fully excavated (Noble et al. 2019b: 69–70). This incomplete investigation and poor preservation meant that it was not possible to address their exact form or function, and conclusions relied largely on material culture assemblages.

Given this paucity of evidence, the recent discovery of a potential urban metropolis at the hillfort of Tap O'Noth, which overlooks the settlement at Rhynie, is of immeasurable significance. The site is a vitrified Iron Age fort with a dense concentration of over 800 hut platforms, originally believed to be Bronze or Iron Age in date (RCAHMS 2007: 101–105; O'Driscoll 2020). Though investigation of the inner fort failed to produce any evidence of early medieval reuse, excavation of the outer fort (including two of the hut platforms) unexpectedly returned third to sixth century AD dates (O'Driscoll 2020; Noble and Evans 2022: 66). At present the evidence is too limited to comment further however, if future investigation supports these findings, the site would stand as the one of the largest forts and native settlements across Britain and northwest Europe, completely rewriting the narrative of early medieval settlement in Scotland (O'Driscoll 2020). The reuse of Iron Age sites has already been mentioned above, and whilst the role of memory in recycling landscapes is a relatively recent development within early medieval studies (see Williams 2006; Semple 2013; Williams et al. 2015; Fentress 2018), excavations such as this have immense potential to develop our understanding of the social and political implications of Pictish settlement.

However, the generally poor survival of structures within fortified settlements means that there remains an area of research for which we have very little evidence – daily life. Wainwright (1955b: 87) first acknowledged this issue in *The Problem of the Picts*, noting that a "study of Pictish dwellings and their contents would throw much light on the Picts". Some 62 years after Wainwright's original statement, the issue remains largely unchanged, with Alex Woolf declaring "what we don't know about the Picts, and what we need to know, is how ordinary people lived…what we really need is more lowland, rural settlements to be excavated" (Woolf 2017).

2.4.2. Unenclosed settlement

Pictish dwellings located outwith fortified or enclosed settlements are sparse and evidence of their possible whereabouts, particularly across Moray and in the lowland areas of eastern Scotland, remain elusive (Fraser and Halliday 2007: 115). House forms in eastern Scotland appear to have little in common with known examples on the Western and Northern Isles and it is not possible to simply recognise a Pictish house in the landscape (Carver et al. 2012: 191; see Ralston 1997; Geddes 2006; Dockrill et al. 2010). Much of our understanding of unenclosed settlement has therefore come from a handful of excavated examples in eastern central Scotland. As such, the evidence base has limited geographic range and the fact remains that only a very small number of dwellings have been subjected to thorough archaeological investigation.

One of the earliest excavations was conducted in 1989 at Easter Kinnear in north-east Fife. Unusual cropmarks revealed a series of shallow ditches and an associated sub-rectangular, almost square, scooped structure, which had been abandoned, filled, and reoccupied by a sequence of up to five wattle-and-daub constructions (Driscoll 1997; Fig. 2.3). Although no floor was recovered from the scooped feature, a lack of silting indicated it had been roofed and was likely a storage area within a timber superstructure. Radiocarbon dating placed the site tightly within the mid-sixth to mid-seventh centuries AD, and similar structures in an adjacent site (Hawkhill, 700m NE of Easter Kinnear) indicated it was part of a small settlement that had been rebuilt and remodelled throughout the early medieval period (Driscoll 1997).

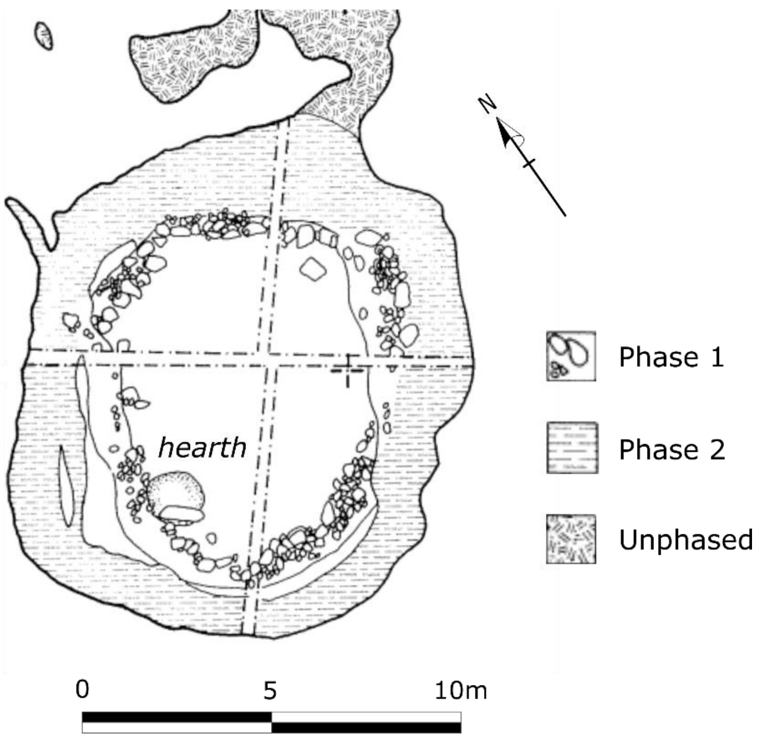

Fig. 2.3. Phased plan of the Easter Kinnear structure (after Driscoll 1997: 84)

Given their position within a fertile valley, it was concluded the sites represented a Pictish farming community of modest or servile status (Driscoll 1997: 113). Their discovery challenged the widely held assumption that most early medieval rural settlement had been obscured by modern farms, and Driscoll (1997) pushed for a reconsideration of where researchers should be looking for this evidence. As of yet, there has been no detailed reassessment pertaining to the Pictish period, although Olivia Lelong's evaluation of where to identify medieval and later medieval rural settlement does offer a valuable starting point (Lelong 2003). It suggests focusing on sites that were not repurposed in the nineteenth century, but rather abandoned during the medieval period. The two sites put forward in support of this argument are Pitcarmick and Carn Dubh.

Pitcarmick is an upland site in Perthshire and constitutes the most well-known evidence for lower status dwellings and rural settlement. Here, the sub-rectangular plan found at Easter Kinnear can also be identified, although in a far more elongated form (up to 26 m in length) that was constructed in turf and stone rather than timber or wattle. First identified through the RCAHMS (1990) survey, this particular type of structure has come to be known in the literature as a 'Pitcarmick-type building' (Foster 2014: 73–74). Excavation of two parallel structures in 1993–1995 radiocarbon dated their use to AD 700–850 and both were found to have similar layouts, with a residential hearth area in the western end and a byre area with a paved drain (believed to house animals) in the east (Carver et al. 2012: 146, 161; Fig. 2.4). Given their position above the 300 m contour, Alcock (2003: 265) argued that the Pitcarmick houses may have been summer shielings rather than permanently occupied dwellings, though this was not confirmed through excavation.

The Pitcarmick landscape is known to have been inhabited with farmsteads since the Bronze Age, and animal bone evidence indicated that the Picts would have engaged in sheep and cattle husbandry and likely had part of the land under cultivation (Carver et al. 2012: 182, 185). The continuation of rural settlement is demonstrated by a number of field boundaries, furrows and clearance cairns, although it is not yet clear whether any of these can be attributed to the Pictish period. Both excavated houses at Pitcarmick were reused in the eleventh and twelfth centuries and had subsequently been truncated by later medieval and post-medieval ploughing (Carver et al. 2012). Carver commented that a reluctance to excavate the walls limited structural interpretations and precluded an understanding of the natural and anthropogenic processes that had affected them (Carver 2012: 150, 160).

Settlement continuity can be recognised elsewhere in the Perthshire uplands and forms the primary context for rural Pictish dwellings (RCAHMS 1990; Strachan and Sneddon 2016: 6). Both Carn Dubh (9 km NW of Pitcarmick) and Lair (10 km NE of Pitcarmick) contain a concentration of Bronze and Iron Age roundhouses, alongside the associated agricultural remains of field banks and clearance cairns. Excavation at Carn Dubh identified an early medieval house (House 8 – dated c. AD 600–900) that had been constructed from two adjacent Bronze Age roundhouses to form an elongated D-shaped plan, similar to that of the heel-shaped building in Portmahomack (Rideout 1995: 150, 153-155; Fig. 2.4). The use of pre-existing structures was seen to have demonstrated a relationship between prehistoric and early medieval settlement (perhaps mirroring that identified on reused Iron Age forts), although a small excavation area limited structural information and no other early medieval buildings were identified as part of the survey or excavation efforts (Rideout 1995).

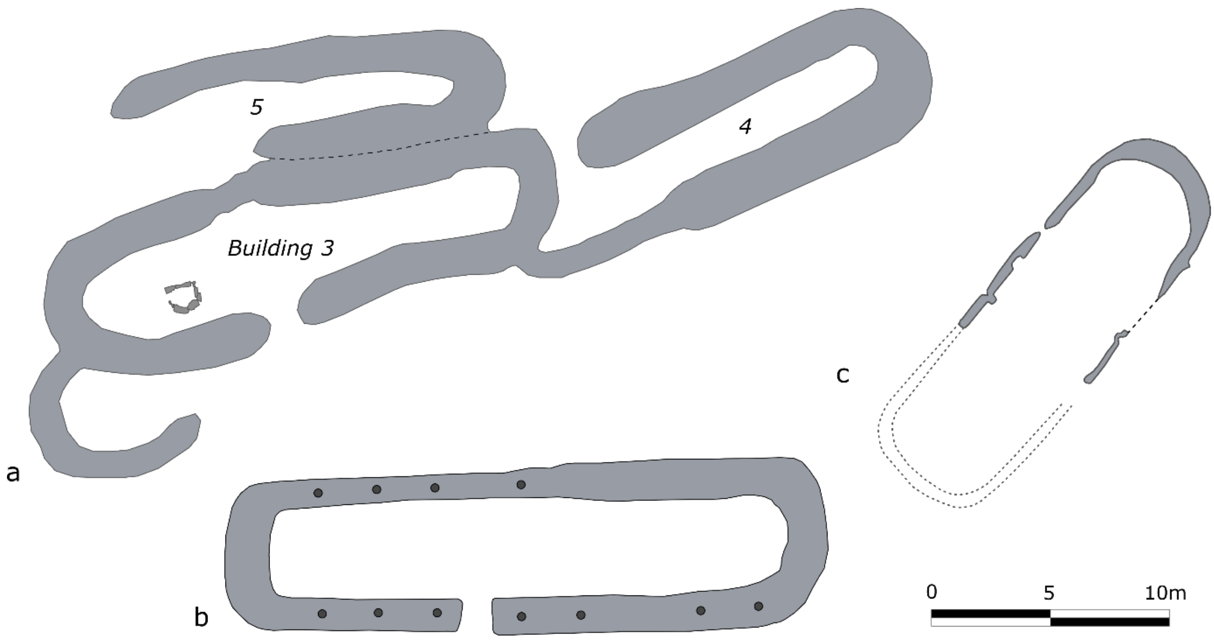

Fig. 2.4. Unenclosed Pictish structure plans (after Noble and Evans 2022): (a) Lair, Perthshire; (b) Pitcarmick, Perthshire; (c) Newbarns, Angus

More recent excavations at Lair have dated seven structures (including three Pitcarmick-type buildings) to the Pictish period (c. AD 600–900), and surveyed several others, all of which are located around a ring-cairn of probable Early Bronze Age date (Strachan et al. 2019; Fig. 2.4). Although primarily constructed in turf, there is again evidence for the reuse of Bronze Age material, with kerb stones from the cairn being used to define the south-eastern edge of Building

2 (Strachan et al. 2019: 37). Construction was found to have varied widely between the structures – Building 2 had substantial stone foundations whereas Building 1 did not; Building 3 had a paved byre end and stone-built hearth, whilst Building 7 had no indication of occupation. The prevailing narrative was therefore a seventh to ninth century farming settlement that included both domestic dwellings and structures that had been reused or purpose-built for animal shelter or storage (Strachan et al. 2019). Further complicating matters was the fact that floor layers were reported to be absent, fragmented and almost impossible to clarify in the field. The reasons for this were unclear and many of the issues observed on enclosed sites regarding internal preservation are also widely present across unfortified settlement, even when there is good preservation of the upstanding elements (see Chapter 6 this thesis). Strachan et al. (2019: 125) have since identified at least 30 additional structures which bear similarities in plan but currently remain unexcavated.

A structure at Newbarns in lowland Angus provides one of the few rectilinear buildings detected outside upland Perthshire and offers a comparison for the Portknockie example in Aberdeenshire (McGill 2004; Dunwell and Ralston 2008: 140; Strachan et al. 2019: 130; Fig. 2.4). Again, preservation was found to be incredibly poor, with shallow structural evidence of a timber-framed building and a floor space almost completely devoid of archaeological remains (McGill 2004). The size and form of the Newbarns and Portknockie buildings are comparative with the sixth and seventh century timber halls and Anglican buildings found elsewhere in northern Britain (see Ralston and Armit 2003: 226–229; Carver 2019: 193; Figs. 2.2 and 2.4), though whether this can be used to discern status of function remains unclear. Dunwell and Ralston (2008a: 140) have suggested that the absence of timber structures of this scale in the cropmark record may indicate it was the home of a local elite rather than a vernacular house form; however, an absence of evidence is a particularly precarious thing on which to hang interpretations. Many examples could have been lost to the plough, and the lack of finds at either site that would support this interpretation is notable.

The Pitcarmick-type buildings, with their turf construction and internal byre, are more frequently compared to longhouses in Scandinavia and the Netherlands, implying a shared connection with settlement around the rim of the North Sea (Carver et al. 2012: 191–193; Carver 2019: 213; Strachan et al. 2019: 129–132). In the initial publication of Pitcarmick, Carver et al. (2012: 191, 194) dismissed a possible relationship with western Scotland, Ireland, and Anglo-Saxon England on account of their lack of combined byre-houses, however an exception has since been identified in an eighth century group in Devon that links England with the Netherland tradition (Beresford 1979; Carver 2019: 213 – see Strachan et al. 2019: 131). Thus, the Pictish structures in eastern Scotland should now form a fundamental part of English and continental discussions. It has also been noted that the emergence of Pitcarmick-type settlement in Perthshire coincided with a warming of temperatures after the end of the Early Historic Cold Period c. AD 600 and comprised both a change in architectural tradition (the construction of rectilinear dwellings) and an expansion onto more marginal ground that had not been settled since the Bronze Age (Tipping in Cook 2015: 15, 20, 52, 55). This may imply some degree of reorganisation in systems of land holding and has been linked to the appearance of underground storage and corn drying kilns at Kintore, perhaps indicating a widespread focus on agricultural production and the storage of surplus that was collected by a centralised polity (Cook and Dunbar 2008: 356–357; Evans 2014 68–75; Cook 2015: 20).

Outwith Perthshire and central Scotland, evidence of unenclosed settlement is more limited, and a large proportion of the dated settlement evidence has come from chance finds in development-led excavations (see Kruse and Noble 2021). These are predominately ephemeral features, such as isolated pits and hearths, which, although significant in tracing Pictish activity, offer relatively little detail regarding domestic life and settlement organisation. Early medieval metalworking activities have been identified at several open sites including Walton Road (Aberdeen – Woodley 2018) and Kintore (Aberdeenshire – Cook and Dunbar 2008), complementing finds on enclosed sites such as Maiden Castle (Cook 2011b). This may indicate that such activities occurred on the periphery of settlements (Cook 2002: 71), however a lack of synthesis on metalworking during this period has so far made interpretations difficult to contextualise (Woodley 2018: 51). In the lowlands, unenclosed settlement remains largely represented by the secondary activity in and around Iron Age souterrains, though this is now primarily interpreted as reflecting opportunistic reuse rather than continuous occupation (Coleman and Hunter 2002; Anderson and Rees 2006). Regional overviews of the evidence for early medieval settlement are being developed as part of Scotland's new archaeological research frameworks and current examples provide a much needed (if not always fully exhaustive) catalogue. Eastern Scotland will primarily be covered by the NE Scotland Regional Research Framework (currently unpublished), however evidence is also contained in the Highland Archaeological Research Framework (Kruse and Noble 2021) and in the Perth and Kinross Archaeological Research Framework (Strachan et al. 2022).

2.5. General trends

Though limited, these discoveries form the foundational understanding of Pictish settlement in eastern Scotland and several trends can be drawn out from the resulting catalogue of sites. First, there is significant evidence for the reuse of prehistoric constructions in fortified settlement across the area, and the evidence from Lair and Carn Dubh also suggests that this was extended to buildings in rural contexts, though to a lesser-known extent. Second, a general shift from round to rectangular house forms can be observed throughout the period (see Dunwell and Ralston 2008a: Clarke 2012: 88; Carver et al. 2016: 288), however explanations for the motivations behind this change are lacking (Driscoll 2011: 263). The question of whether such a thing as a 'typical Pictish house' exists, either in a period or regional sense, also remains unclear. There is a tendency towards assumptions of site date based on structural typologies, and sites such as Tap o'Noth (Noble and Evans 2022: 66–70) and projects such as *The Hillforts of Strathdon* (Cook 2015) have shown that targeted excavations can rewrite interpretations. Third, there appears to be a decline in the use of earth-fast elements, such as posts set into deep pits, in favour of turf construction and other methods that leave more ephemeral signatures in the ground (Ralston 1997: 24; Noble and Prado 2022). Particularly in lowland areas subjected to repeated cultivation, the detection of non-earth-fast timber or turf architecture has proved problematic, and a combination of building materials, reuse, and agricultural attrition are frequently touted as explanations for the lack of Pictish settlement evidence (Wainwright 1955: 88; Ralston 1997: 34; Carver et al. 2016: 228; Noble et al. 2019b: 69; Prado and Noble 2022: 1). Finally, structures are almost always devoid of diagnostic artefacts or coherent stratigraphy that can be used to assess function or status. Even upstanding structures (Pitcarmick, Lair, Litigan, Queen's View) or those that have a semi-sunken interior (Easter Kinnear) have failed to produce clear evidence of floor layers and there is a desperate need to understand why preservation is so poor across different site types and environments (Ralston 1997; Noble et al. 2020: 320; Prado and Noble 2022).

2.6. Methods of excavation and analysis

Many of the outstanding questions regarding site preservation and daily life in eastern Pictland result from the simple fact that archaeological investigation directed at answering them has not been conducted. The first issue lies in the frustratingly small-scale of excavation with which most sites have been approached. The vast majority of excavations have utilised key-hole strategies or transects over ramparts, precluding the identification of interior structures, layout or potential areas of best preservation. Other sites have only been investigated as part of watching briefs (e.g. Mither Tap hillfort in Aberdeenshire – see Atkinson 2006, 2007) or their excavation records remain unpublished (e.g. Craig Phadrig – see McCaig 2014). Wider-scale excavations, including the use of strip-and-map at Portmahomack and Rhynie, have helped to identify structures, however, they are not always subjected to feature-level analysis (Carver 2016; Noble et al. 2019b). Beyond bulk sampling for dating material, very few excavations have employed further multi-proxy environmental and geoarchaeological sampling, such as phytolith analyses or geochemistry. Basic geochemistry (pH, organic matter by loss-on-ignition, and phosphate determination) was conducted at the multi-period site of Carn Dubh, however only one sample (a hearth-deposit) was taken from the Pictish structure and offered little interpretative value (Rideout 1996: 176 and microfiche).

A handful of sites have been examined through micromorphological analyses – a method that involves taking *in situ* blocks of sediments from exposed surfaces and soil profiles and examining them under a microscope (Courty et al. 1989). Investigation of poorly preserved internal deposits in a seventh to ninth century AD rectilinear structure in Kintore, Aberdeenshire, found that the original sediment fabric had been almost completely destroyed by post-depositional soil processes including weathering, bioturbation and compaction (Cook and Dunbar 2008: 299). Despite this, the technique was also able to offer structural evidence and suggested that charred material had likely originated from the burning of a wooden superstructure capped by grass/turf thatch (Cook and Dunbar 2008: 299). Additional micromorphology has been conducted on internal deposits in the excavated hut platforms at Tap o'Noth, with early results indicating that they display little stratigraphy and very poor levels of preservation (Gordon Noble pers. comm.). These results have not yet been published and cannot be commented on further.

Most recently, Prado and Noble (2022) have used phytolith and diatom analysis to identify turf walling and roof deposits in Cairnmore fort, near Rhynie. As at Rhynie, settlement remains were poorly represented and later cultivation had appeared to remove the majority of floor layers. The exception was a dark brown floor deposit over 6 m in diameter and up to 0.12 m in depth that appeared to form part of a circular roundhouse structure. Concentrations of microalgae and wetland phytoliths around its perimeter suggested the use of nearby wetlands for turf walls, whilst grass and aster phytoliths were more tentatively interpreted as thatched roof deposits of dried grass and heather (Prado and Noble 2022: 7–8). More strikingly, the authors attempted to use these proxy methods to ascertain internal activities such as food-processing and bedding areas. There are significant pitfalls associated with such an approach, namely that post-depositional processes are highly varied depending on the soil type and should be investigated separately for each study (Shillito 2013: 79). Phytoliths cannot simply be assumed to occur as a result of *in situ* decay, particularly when they are known be highly mobile under certain conditions (Iriarte 2003; Itzstein-Davey et al. 2007). For example, in a sandy sediment with high rainfall (similar conditions to those encountered in the Rhynie area), 22% of phytoliths were found to have leached from their layer (Fishkis et al. 2009). Though the authors acknowledged the admixture of roof and floor deposits, and that taphonomic processes can contaminate and alter assemblages (Prado and Noble 2022: 8, 11), the fact that micromorphology was not used to confirm these processes or assess the integrity of the floor deposits fundamentally undermines the findings.

The reason for such a lack of engagement with geoarchaeology is related to a combination of factors. The tradition of archaeological excavation in the area has not lent itself to its application; geoarchaeology is not written into the development process and very few commercial excavations have employed its techniques. Prominent excavators have also failed to fully engage with the methods and principles, and there has been an unfortunate acceptance that little detail can be gleaned from poorly preserved occupation deposits. This is not true across all of Scotland and the geoarchaeological investigation of Pictish structures has proved far more lucrative in the Western and Northern Isles. Micromorphology and geochemical analysis conducted at the farmstead site of Bornais, for example, has provided evidence of floor formation, food consumption and maintenance practices (Milek 2012c; Sharples 2012 – see Chapter 3, section 3.1.4).

2.7. Heritage at risk

Across much of the world, significant archaeological remains are protected by national governments. The European Convention on the Protection of the Archaeological Heritage (the 'Valletta Treaty'), of which the UK is a signatory, requires states to make provisions "for the conservation and maintenance of the archaeological heritage, preferably *in situ*" (Council of

Europe 1992, article 4ii). Within Scotland, this is implemented in a number of ways. The first tier of protection falls under the Scheduled Monuments and Archaeological Areas Act 1979, which makes it a criminal offence to disturb significant remains (as defined by Historic Environment Scotland) without pre-approved consent through the Scheduled Monument Consent Procedure (Scotland) Regulations 2015 (UK Government 1979, 2015). Monuments are excluded from development and are further protected by the Ancient Monuments (Class Consents) (Scotland) Order 1996, which limits damaging land use strategies but cannot control agricultural practices if they are shown to have occurred on the land within the previous ten years (UK Government 1996). Additional protection is held in planning policy and guidance, such as the Scottish Planning Policy and Planning Advice Note 2/2011 (Scottish Government 2011). These are implemented by a range of local authority advisory services and seek to preserve archaeological sites, monuments, and their settings *in situ* wherever feasible.

However, recognition of the threat posed by climate change has recently prompted a re-evaluation of the way Scottish heritage bodies approach site preservation (see Harkin et al. 2017, 2019). The widely held assumption that archaeological material is best preserved *in situ* has been challenged and new documentation has explored the need for heritage managers to adapt their approach and follow either a *resistance* (actively seeking to halt/reverse the impact) or *acceptance* (ensuring successful management before loss occurs) response (Harkin et al. 2019: 15). To plan the most appropriate action, it is therefore imperative to have a firm understanding of the most significant threats to a cultural resource (and their susceptibility to these factors) to assess the challenges posed by future changes. However, much of the research into risk management has typically concentrated on visible and upstanding heritage remains (see Harkin et al. 2017), with considerably less attention being afforded to buried material (for example, sites which exist as cropmarks). There is still very limited information on both the rates of degradation in particular burial environments and the impacts that are occurring at individual sites. Rarer still are studies which focus on the impacts of this degradation on soil features such as pits, ditches, floor surfaces and anthropogenic soil horizons.

Poor preservation can result from a myriad of physical, biological and chemical agents that serve to destroy the archaeological record (English Heritage 2011, 2012; Historic England 2016a). Agriculture, coastal erosion and acidic soils are all commonly cited as reasons for the poor preservation of Pictish settlement but very few of these factors have been explored in detail or on any significant geographic scale. Furthermore, there are significant settlement sites –

including the structures at Lair – which have not been scheduled and are currently unprotected by the Scottish government. Pictish settlement offers a unique window into early medieval society but the limited number of known sites means that the opportunities to access this information are waning. Given the ongoing threat posed by preservation factors and climate change, the ability to predict sites most at risk of alteration (or those that currently have the best examples of preservation) will be critical in ensuring effective management and investigation.

2.8. Creation of a *terra incognita*?

Returning to the idea of a Pictish *terra incognita*, we can identify several contributing factors in the evidence presented above. There is a clear topographic imbalance that has favoured the identification of sites and structures in prominent hilltop and coastal locations or upland rural environments, resulting in a relative dearth of lowland settlement. Are we seeing a fundamental shift in settlement patterns during this period or is it a genuine reflection of survival? Similarly, is the absence of enclosed settlement in Perthshire and Angus related to topography, survival and/or research agendas, or is it indicative of a nucleation of power concentrated further north? A persistent focus on high-status sites (particularly in the north) continues to drive such contrasts and has been exacerbated by a reliance on suspected site types and architectural forms, which themselves are based on a very small corpus of geographically skewed sites. Cook (2012, 2015: 54) has also observed that the very nature of mitigation excavation, heritage guidance, and practice ensure that the picture remains incomplete. Known sites are either avoided by development to preserve them *in situ* (as per Scottish Planning Policy; Planning Advice Note 2/2011), or only partially excavated to retrieve the minimum level of information required (as per The Scheduled Monument Consent Procedure (Scotland) Regulations 2015). Finally, the lack of detailed investigation into site preservation means that many of the interpretations regarding settlement absence have not been substantiated, nor have those few examples with surviving deposits been thoroughly tested for evidence of Pictish activity.

This combination of research agendas, survey limitations, and restricted excavation methods means that perceptions of eastern Pictland as a *terra incognita* persist, regardless of their tenuous or untested nature: they are perpetuated simply due to an absence of information. This is intimately linked to our understanding of lower status settlement, which remains isolated from larger social and political narratives. As such, the degree to which these gaps in the settlement record are the result of ephemeral techniques of construction, post-depositional destruction, or inherent biases in the methods of archaeological analysis remains unclear. An evaluation of factors affecting the survival and identification of early medieval remains is thus likely to offer much needed direction on the study of eastern Pictish settlement.

In a review of the issues facing Pictish research, Driscoll (2011) commented that Pictish settlement studies must move towards more structural and systematic investigations. This, he argued, required a shift away from site-based approaches to landscape analyses that prioritised inter-relationships and organisational frameworks (Driscoll 2011: 263–264). Such approaches are undoubtedly of value; however, in the decade following his assessment, progress in making such connections has been relatively limited. We are still restricted by a poor knowledge of the roles that structures and settlements played or, in many cases, where these sites are located. The lack of understanding regarding daily life, site preservation, and the influence post-depositional factors have had on the Pictish settlement record needs to be addressed, and there is no reason why site-based approaches should be dismissed. In fact, it is likely to be far more productive if we consider these two methods as complementary. We need to first establish a foundational understanding of the survival, preservation, and depositional history of these sites (both regionally and at a site-based level) if we are to meaningfully move forward with broader narratives. The geoarchaeological methods that can be used to establish this understanding form the focus of the following chapter.

3. Methods

3.1. Methodological framework

Emerging largely from the work of Michael B. Schiffer, formation theory has had a profound impact on both the theory and methodology of archaeological practice (Schiffer 1983, 1985, 1987 – see Lucas 2012 for a review of major theoretical developments). In short, it posits that the archaeological record is not a snapshot in time but rather an assemblage of materials that have undergone various natural and cultural transformations before, during, and after human activity (Shahack-Gross 2017: 37 – see Schiffer 1983, 1985, 1987). Understanding the processes which affect this assemblage – 'site formation processes' – is therefore of fundamental importance to archaeological interpretation (Schiffer 1987; Goldberg et al. 1993; Stein 2001; Holliday 2004: 261–337). Of equal significance is the archaeologist's ability to differentiate between authentic residues of the past and the processes that have subsequently altered their composition.

Site formation processes lie at the very heart of geoarchaeological theory and methods. Geoarchaeology is devoted to understanding the reflexive relationship between humans and the natural world, and how one has shaped the other (Wilson 2011; Cordova 2018). Archaeologists have always been mindful of the environmental context of past human activity, however geoarchaeology as a distinct discipline is generally considered to have emerged in the 1970s as part of the New Archaeology movement that advocated for systematic integration of the data and perspectives of the sciences (Butzer 1982: 4; Wilson 2011: 2; Cordova 2018: 11, 24). Geoarchaeology is therefore an amalgamation of the theory and techniques of multiple disciplines and blends the culture-centered questions of archaeology with the more empirical data of geomorphology, geology, and soil science (Canti 2001; Cordova 2018). It incorporates field, desk and laboratory-based work which occurs at all scales of analysis, from the largest of landscapes right through to site-based analysis at the microscale (Butzer 1982; Cannell 2012: 35–36). It is within this broad and multidisciplinary approach that the methodologies of this thesis have been developed.

This thesis employs a combination of literature analysis and desk-based assessment to assess site formation processes at a regional scale. It also utilises integrated geoarchaeological analyses to understand their impact at the site-level and evaluate the ability of these techniques to provide new insights into early medieval activity in domestic structures. These approaches represent a methodological and theoretical departure from Pictish settlement studies in eastern Scotland and draw on a number of comparative studies from other geographic regions.

3.1.1. Regional assessments

Regional assessments of the processes that affect site preservation are becoming an increasingly important aspect of archaeological and heritage research agendas. They permit a broad consideration of interacting threats that cannot always be achieved by more time-consuming and labour-intensive site-based investigations. They also counteract some of the pitfalls associated with site-level approaches, which become less practical over wide areas and less workable as site numbers increase (Heilen et al. 2018: 264; Fenger-Nielsen et al. 2020: 1281). Efforts to date have primarily concentrated on understanding the extent to which the survival of known archaeological sites is representative of a region's wider record and how this can be used to inform subsequent management procedures (Lovis et al. 2012: 591). Many approaches have grounded themselves in the general findings of past excavations and used this to launch systematic programmes of geological, geomorphological and field soil data-gathering to inform assessments of preservation (e.g. Monaghan and Lovis 2005; Oxford Archaeology 2006; Lovis et al. 2012; Hollesen et al. 2017). Others have utilised geographic information systems (GIS) to model resource values and develop risk maps of prospective threats. Risk maps offer a valuable resource for heritage management but tend to concentrate on upstanding remains and the impact of natural disasters (Accardo et al. 2003; Scalet et al. 2014; Wang 2015), urbanism (Agapiou et al. 2015) or the long-term effects of pollution, tourism, erosion and climate change (Accardo et al. 2003; Paolini et al. 2012; Wu et al. 2014; Heilen et al. 2018). By comparison, very few efforts have mapped risks associated with buried heritage or changes to the burial environment.

Regardless of their focus on upstanding or buried remains, very few studies have used pre-existing excavation literature as their primary data for qualitative and/or quantitative regional preservation assessments. A notable exception is Rick et al.'s (2006) qualitative survey of taphonomy and site formation on California's Channel Islands, which draws on their own excavation experience as well as published and unpublished excavation reports. The overriding focus of the article is the impact of burrowing animal activity, however the authors also demonstrate the destructive effects of other natural and cultural agents such as agriculture, floralturbation, marine processes and historical disturbances. Information is presented in clear tables that synthesise the post-depositional processes and demonstrate their observed impact on archaeological sites in the region. Though the study is non-exhaustive, the review provides a foundational base for understanding post-depositional processes in the area and demonstrates the value in narrowing the evidence base, as it permits a more comprehensive discussion. Notably missing, however, is an equally coherent synthesis of the sites and literature from which these observations have been drawn. References are embedded in the text, but a catalogue of citations or semi-quantitative assessment of impacts would provide a welcome database for the reader. The main takeaway from the survey is that, even in areas with seemingly good preservation, numerous cultural and natural processes are actively degrading the regional archaeological record (Rick et al. 2006: 583). The authors argue that acknowledgement of this issue, supported by a clear evidence base, should prompt the establishment of multi-scaled frameworks for investigating site preservation in any regional zone. They also caution that a lack of geoarchaeological research is likely to impair archaeological interpretations and result in unwarranted confidence in assessments of cultural and environmental change (Rick et al. 2006: 584).

Fenger-Nielsen et al.'s (2020) multi-threat assessment of archaeological sites in south-west Greenland forms another methodological foundation for the regional surveys presented in this thesis. The inspiration here comes from their use of open and publicly available datasets on air temperature, soil temperature, vegetation, and shoreline changes, alongside site-based archaeological evidence, to assess threat levels imposed by climate change. They found that threat levels varied within the study area due to variations in the region's topography and a west–east climate gradient. Though the region does not provide a clear analogue for eastern Scotland, it was notable that the most critical zones were found in lowland areas and related to microbial degradation as a result of increasing summer temperatures (Fenger-Nielsen et al. 2020: 1291–1292). The authors also identified that the use of generalised datasets had certain limitations, the most significant being an inability to pinpoint individual sites at risk. They concluded that this could only be achieved if the accuracy and spatial resolution of risk estimates was improved through detailed site-based knowledge regarding the relationships between environmental conditions and degradation processes (Fenger-Nielsen et al. 2020: 1294).

Within Scotland, demand for regional preservation assessments has been established in the Scottish Archaeological Regional Research Frameworks (Kruse and McCullagh 2021 for HARF; Reid and Roy 2022 for PKARF). Recommendations for future research include the need to assess regional taphonomies and settlement patterns, and their relationships with soil-types, geology, and land use through time (HARF Qu 3.16; PKARF Qu. 9.21 and 9.27). The frameworks also call for assessments of the major threats to site survival (PKARF Qu. 9.28 and 9.29), as well as how land use and post-depositional processes have influenced the identification of settlement (PKARF Qu. 9.21).

Given the lack of regional assessments that have concentrated on impacts in the burial environment, this thesis set out to assess the value of publicly available national soil datasets for informing such approaches. Soil maps based on systematic soil surveys contain a wealth of data on landscapes as well as soil properties but are rarely used in geoarchaeological investigations (Holliday 2004: 53 – see Holliday 2004: 53–71). To date, only a handful of studies have applied national soil survey data to the archaeological record, but their focus has primarily been on site prospection (e.g. Dekker and Weerd 1973; Almy 1978; Warren et al. 1981; Layzell and Mandel 2019) and similar efforts have not been extended to an assessment of heritage at risk. Their investigation in eastern Scotland, presented in Chapter 4 (Reid and Milek 2021), functions as both a regional assessment and a methodological proof of concept.

3.1.2. Site level assessments

Due to the frequency with which archaeological sites are excavated, site level investigations of preservation have by far outnumbered regional assessments. They provide a higher quality of data, both in resolution and nuance, and are extremely useful for establishing baseline records (Heilen et al. 2018: 264; Fenger-Nielsen et al. 2020: 1281). The ways in which archaeological sites can be impacted by natural and cultural processes has been established through numerous studies and excavations (see Goldberg et al. 1993; Stein 2001; Oxford Archaeology 2002, 2010; Holliday 2004; Davidson and Wilson 2006; Goldberg and Macphail 2006; Karkanas and Goldberg 2019 – see also Appendix 1). This is supplemented by experimental work and detailed ethnoarchaeological studies that have specifically concentrated on understanding the geoarchaeological signatures that result from these processes (Goldberg and Whitbread 1993; Middleton and Price 1999; Milek 2006, 2012b; Wilson et al. 2008, 2009; Friesem et al. 2014a, 2014b; Banerjea et al. 2015 – see Friesem 2016).

Geoarchaeological methods of assessing preservation at the site level vary. Many geological and biological agents are identified in the field simply through landscape assessments and the field-based descriptions of soil or sediment composition (Goldberg and Macphail 2006; Karkanas and Goldberg 2019). Coastal erosion, animal burrows, and tree or plant roots can be easily recognised through these methods, whilst a trained eye is able to identify deposits resulting from slope, wind, or water action (Goldberg and Macphail 2006; French 2015: 69–73; Karkanas and Goldberg 2019). Field observation is also the primary method of identifying major anthropogenic impacts such as reuse and agricultural truncation (Dunwell and Ralston 2008b; Karkanas and Goldberg 2019). Numerous studies have enhanced these interpretations through micromorphological analysis to detect more diagnostic features including microstratigraphy, microstructures, and the inclusion of exogenous material (Macphail and Goldberg 2018a). Some alterations to soil chemistry can also be recognised in thin-section (Milek and French 2007: 324–325), whilst other assessments such as soil acidity are approached through laboratory analysis and the use of systematic bulk sampling (Holliday et al. 2004; Historic England 2015). Many studies have demonstrated that the highest quality assessments are achieved through a combination of multiple techniques and multiple scales of analysis (Enloe 2006; French 2015: 83–87; Howard et al. 2015; Historic England 2016a, 2016b; Stratford et al. 2022).

However, whilst detailed assessments of preservation at the site level *can* be achieved, comprehensive understandings are limited by the degree to which they are applied. The lack of geoarchaeological work across eastern Scotland's early medieval record has already been established and speaks to a much wider omission of the discipline within the region (see Historic Environment Scotland 2018; Reid and Roy 2022). This is not for lack of detail, nor is it at the expense of studying past people, as when multiple methods are integrated these techniques have the added benefit of being able to detect cultural practices and inform the interpretation of activity areas.

3.1.3. Activity area analysis

Activity area analysis operates on the basic principle that the distribution of objects and residues reflects the use of space through human action (Pfälzner 2015: 29 – see Kent 1987, 1990). Thus, occupation deposits and their associated assemblages can provide information on the organisation of space, the types of economic and maintenance activities that governed daily life, and the changes that occurred in these practices during the abandonment or reuse of a structure (Carr 1984; Gé et al. 1993; LaMotta and Schiffer 1999; Macphail et al. 2004; Milek 2012b).

There are a number of important caveats to spatial interpretations of household deposits. First, the distribution of archaeological material is not only determined by depositional practices but also cultural processes that remove or relocate particular artefacts and residues. For example, sweeping, pick-up cleaning, and everyday kicking and scuffing, horizontally displace items and only small particles which become embedded in sediments through trampling are likely to remain close to their primary point of deposition (Murray 1980; Kent 1981; Behrensmeyer et al. 1986; Nielsen 1991; Banerjea et al. 2015: 97–98). Milek (2006) reported that large artefacts were almost completely absent in the floor sediments of an ethnographic Icelandic turf house, and that material remains were limited to charcoal fragments less than 2 cm in size, bone fragments less than 2 mm in size, silt-sized ash residues, and the microscopic residues of plant matter and animal dung (Milek 2006: 78, 2012b). Similarly, objects which have become broken, chipped, or obsolete in their current function may be reused within alternative contexts and locations (Deal and Hagstrum 1995). Planned abandonment or reuse of a structure can also force a change in normal cleaning practices, resulting in the accumulation of refuse or the creation of specialised refuse areas (Guttman et al. 2003: 3). Occupation signatures are known to be impacted by the removal or reuse of previously deposited sediments, and several studies have identified microscopic evidence for the use of floor coverings (Gé et al. 1993: 155–156; Boivin 2000; Milek 2012b: 134; Macphail and Goldberg 2018a: 226–234, 2018b: 790). Once abandonment has occurred, collapse is likely to introduce roof material to floor surfaces, potentially obscuring contact stratigraphy in the field and resulting in mixed roof-floor assemblages that encourage bioturbation (Goodman-Elgar 2008; Sharples 2012). Alternatively, roof material may have been removed, exposing floor surfaces to the elements and accelerating natural processes such as leaching and organic decay (Banerjea et al. 2015: 105).

This brings us to the second caveat, which is that occupation surfaces are subjected to the same physical, biological and chemical processes that affect local soils. Some of these processes can favour preservation through conditions such as waterlogging (e.g. Crone 2000; Crone et al. 2018; Knight et al. 2019), however the majority are involved in the disturbance of sediments and the destruction or redistribution of artefacts. The main degradation process for organic material is biological oxidation by soil fauna, thus organic artefacts or structural components are likely to be destroyed in sites where aerobic and moist soil conditions prevail (Kibblewhite et al. 2015: 250–251). The deposition of organic matter through leaf fall or faecal matter can also alter pH levels, changing preservation conditions in the surrounding sediment (Rowell 1994: 153–157; Shahack-Gross et al. 2004; Karkanas and Goldberg 2010: 529-530). In wet climates, percolating rainwater encourages a change in chemical signatures by dissolving and redistributing elements downwards through a sediment in a process known as 'leaching' (Holliday et al. 2016: 44, 864, 870). Podzolisation (a process of B and E soil horizon formation that involves the leaching of metal cations) is particularly damaging to archaeological material and can obscure stratigraphy and feature boundaries (Holliday 2004: 267–268). Calcareous materials are also more prone to dissolution and preserve better in alkaline soils, causing ash, bone and teeth to be largely absent on sites with wet, acidic, and free-draining conditions (Goldberg and Macphail 2006: 68–69; Kibblewhite et al. 2015: 250). Finally, plant and animal activity are the primary agents of mechanical reworking in soils and sediments that results in the homogenisation of archaeological deposits, obscuration of feature boundaries, and the vertical and horizontal displacement of macro- and microartefacts (Wood and Johnston 1978; Erlandson 1984; Davidson et al. 1999; Tryon 2006; Rapp and Hill 2006: 100–101; Kooistra and Pulleman 2018).

As a result, field descriptions of stratigraphy and the distribution of artefacts greater than 2 cm in size can provide insufficient or misleading evidence of activity areas. Equally, trying to interpret microrefuse or geochemical data purely from features or random grab samples is unlikely to provide an accurate portrayal of activity within a structure (Ullah 2012: 124). This is particularly pronounced in poorly preserved buildings, where an absence of constructed features, such as hearths, storage pits or walls, preclude obvious indicators of the agents and processes that governed the use of space. Even in better preserved structures it can be difficult to identify more ephemeral partitions such as wattle divides or 'cognitive barriers' such as low sills, furnishings, or differences in cleanliness (Milek 2006: 26; Negre et al. 2016). It is therefore essential to develop a robust analytical framework capable of detecting and interpretating the possible palimpsest of cultural and natural processes that formed occupation deposits (Milek 2012b: 119).

3.1.4. Integrated geoarchaeology

In light of these conclusions, this thesis aimed to analyse Pictish settlement structures using integrated geoarchaeological methods at a high spatial resolution. Numerous researchers have advocated for such multi-method approaches and successfully applied these to an array of structures and features (Killick and Moon 2005; Sharples 2005, 2012; Milek 2006, 2012a, 2012b; Milek and French 2007; Jones et al. 2010; Milek and Roberts 2013; Shillito et al. 2014; Broderie et al. 2020; Reidsma et al. 2021). Of these, focus can be drawn to two particular case studies – Sharples' (2012) investigation of a Pictish period house on the island of South Uist in Scotland, and Milek and Robert's (2013) study of a Viking Age longhouse in Iceland.

Prior to the completion of this thesis, the investigation on South Uist represented the only known high-resolution geoarchaeological case study of a Pictish period structure in Scotland. Field investigation of an artificial settlement mound at Bornais identified a fifth to sixth century AD building that had burnt down and been rebuilt on at least one occasion, before being abandoned and subsequently stripped of structural elements (Sharples 2012: 42). Only short sections of the wall had survived and the ground plan was cautiously inferred by the vestigial remains of the occupation deposits (in a similar manner to the structure at Burghead – Chapter 7). It was concluded that the early remains likely represented a wheelhouse with a maximum internal diameter of c. 6.4 m, but that this had been rebuilt to form a structure with a rounded east end, two straight sides and a straight west end – the latter representing a similar ground plan to the Burghead building (Sharples 2012: 49, 54; Fig. 3.1).

Systematic grid sampling of the later occupation deposit (a compact orange-red sand) was conducted at 0.5 m intervals (Fig. 3.1). This is one of the highest resolution sampling strategies used in spatial geoarchaeological investigations and was specifically chosen to aid excavation of the commingled occupation deposits and accurately locate material present within the layers (Sharples 2012: 29, 53; French 2015: 94). Copious distribution maps of artefacts, microrefuse and geochemical analyses attest to the variety of material gained through the intensive sampling procedure, however their interpretational value was undermined by several fundamental problems. First, the authors asserted that that because the distributions of artefacts and microrefuse did not show clear patterning across the surface, they provided very few indications for the use of space (Sharples and Norris 2012: 69). This speaks to an underlying assumption that the house or its activities were separated into defined areas and that these demarcations (physical or otherwise) remained the same across space and time. Neither houses nor households are static and are susceptible to changes in use and configuration as a result of social dynamics, cultural practices, and the introduction or abandonment of certain materials (Milek 2006: 25; Ullah 2012; Carpenter and Prentiss 2022).

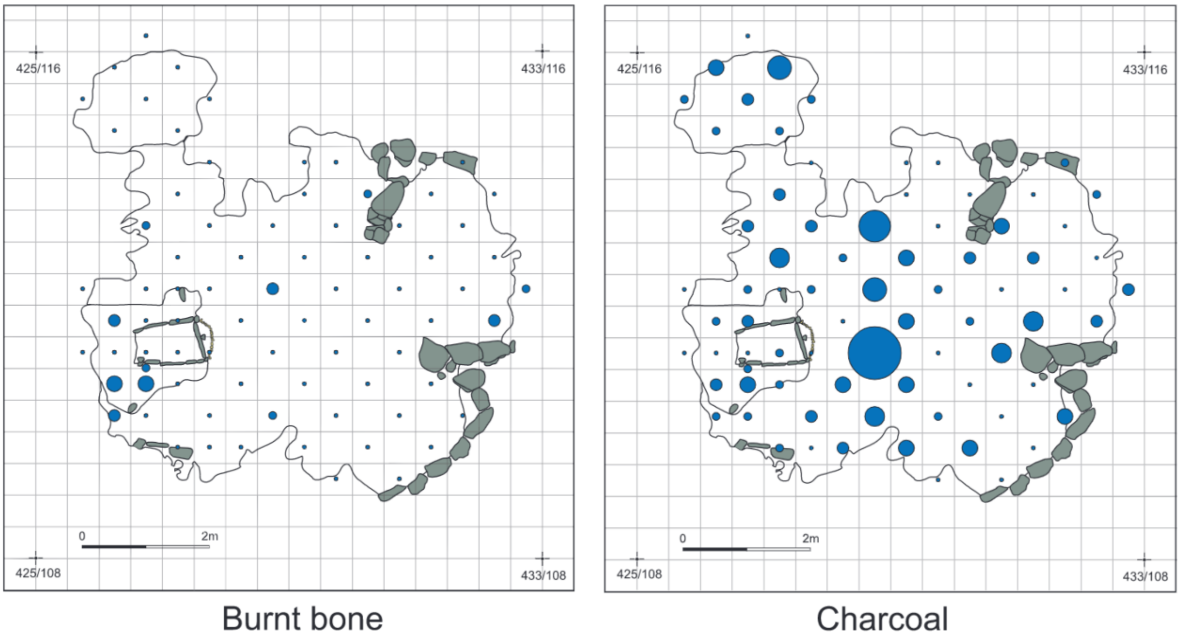

Fig. 3.1. Distribution maps at Bornais showing ground plan of later house floor and density of burnt bone and charcoal material below 10 mm (adapted from Sharples 2012: 71, Fig. 49)

Similar issues were encountered with the magnetic susceptibility and multi-element analyses, whose interpretation was almost exclusively limited to characterisation of the elevated hearth signature (Smith and Marshall 2012: 73). Areas that do not show enhancement can provide just as much information on the use of space as those with elevated readings, but there was little attempt to understand how the wider geochemistry results may have related to the use of space. There were also very few efforts to integrate them with the artefact and ecofact datasets; for example, an elevation of Cu, P, Zn and S appeared to correlate with the mapped distribution of charcoal, mammal bone and coprolites but was not discussed (Smith and Marshall 2012). A more significant failing, however, was the lack of clarity regarding sample integrity and how post-depositional processes may or may not have affected the assemblage. Charcoal and bone are believed to play a role in both the loading and post-depositional retention of Cu, P and Zn, and the soil element concentration patterns are likely related to these distributions and processes (Davidson et al. 2007; Wilson et al. 2008). Milek (2006: 86–87) has also stressed that it is not possible to use the distributions of bone, ash residues or phosphorus to interpret activity areas unless soil acidity is also known, given that it is a major factor in determining their survival. Differences in pH can occur even at the microscale and the absence of any corroborating assessments of pH at Bornais ultimately undermined the validity of the findings.

Micromorphology, which supplemented the chemical analyses, proved to be more successful in providing information regarding formation processes and surface integrity. Despite the lack of structural remains, the occupation deposits were well-preserved and seemed to have been deliberately protected from destruction during rebuilding and stone robbing (Sharples 2012b: 102). Rather than representing a single deposit, the house floor was found to be composed of multiple depositional events, recognised in thin-section by significant differences in colour and composition (Milek 2012c: 61). The deliberate dumping and trampling of peat ash was represented by a bright orange lens containing rubified iron nodules and abundant phytoliths. An organic lens rich in phosphatic material was overlain by a grey sandy lens containing very little anthropogenic material and was interpreted as evidence of a maintenance practice in which clean sand was laid to cover faeces and refresh the floor (Milek 2012c: 61). It was also recognised that in certain areas the floor was indeed commingled with the earlier destruction layer, which had likely been dumped during digging activities associated with the reconstruction of the house and subsequently reworked by bioturbation.

The geoarchaeological investigation of the Pictish period structure at Bornais therefore provides a useful reference point for understanding formation processes and domestic practices in early medieval structures in Scotland – particularly for the building at Burghead, which shares both a similar ground plan and lack of structural detail. This latter point is significant, as the Bornais study demonstrated that buildings with poorly preserved exteriors could retain well-preserved internal deposits. When studied through micromorphology, these deposits provided a level of detail into site formation that was not achievable in the field or through chemical analysis. However, the study also highlights several pitfalls associated with the characterisation of depositional and post-depositional processes, namely that there is little value in viewing artefact and geochemical datasets separately. The inability of the authors to fully interrogate their own spatial data demonstrated the need to rigorously overlap datasets and substantiate multi-element data through additional geoarchaeological techniques, such as pH and organic matter content.

Whereas Bornais provided a comparative ground plan for the structure at Burghead, the building at Lair appears to have more in common with a Viking Age longhouse (Aðalstræti 16) analysed by Milek and Roberts (2013). Both structures were constructed in turf with elongated walls and rounded ends, had surviving internal features including hearths and postholes, and contained field evidence that indicated partition of the interior space for the housing of animals. As previously discussed, similarities have been drawn between Pitcarmick-type buildings and Scandinavian longhouses, and this example provided a potential analogue for geoarchaeological investigation at Lair.

The sampling strategy employed at Aðalstræti was broadly similar to that at Bornais, though it utilised 1 m grid intervals rather than 0.5 m owing to the larger size of the excavation area. The Icelandic structure was also analysed using a number of additional techniques, including pH, electrical conductivity (EC) and organic matter content. The overriding difference in this study, however, is that it went much further in its interpretation of the chemical data. Whereas interpretation at Bornais simply identified patterns in the distribution of geochemical datasets (and primarily focused on one area of enhancement), at Aðalstræti the results of each method were discussed individually before being fully integrated to understand post-depositional events and detect activity areas across the structure. Basic statistical investigation using a Spearman's correlation table was also employed to try and characterise inputs; for example, when electrical conductivity detected an area with enhanced soluble salts, the correlation table suggested this had resulted from Mg^{2+} salts and that sea salt or seaweed were likely to have been used or stored in that area (Milek and Roberts 2013: 1861). There was also greater integration with the micromorphological findings, which helped to confirm field and artefact evidence whilst providing new information regarding fuel types, maintenance practices and the use of space.

The Icelandic example is therefore testament to the value of integrating geoarchaeological methods and results and has been lauded as an exemplary study (Canti and Huisman 2015: 100). It demonstrates how variable pH and EC values can be across a site (Fig. 3.2) and showed that, on their own, distributions of artefacts, charcoal and bone provided only limited insight into the use of space. As at Bornais, micromorphology was by far the most powerful technique in elucidating information regarding activity areas, organic and inorganic inputs, and the preservation and integrity of the occupation deposits (Milek and Roberts 2013: 1863). It is also worth noting that the authors' interpretations relied solely on intrasite variability rather than absolute values, as they were unable to source suitable control samples within the restricted excavation area in Reykjavik city centre.

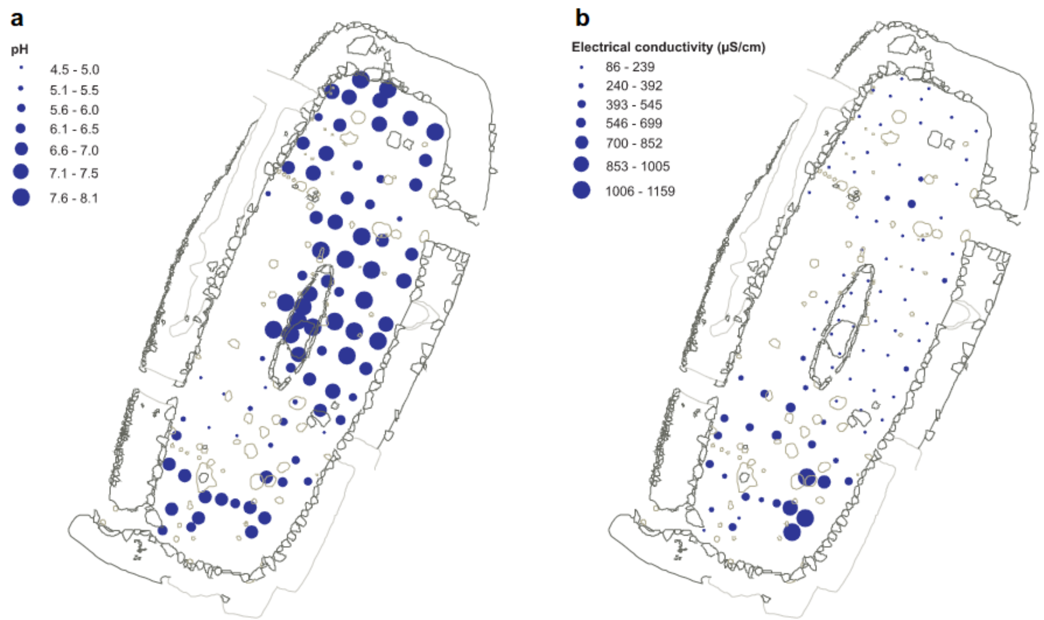

Fig. 3.2. Point mapping of pH and electrical conductivity (EC) results at Aðalstræti 16 (Milek and Roberts 2013: 15, Fig. 5)

Mapping over occupation surfaces remains the primary method of presenting spatial geochemical data (Negre et al. 2016: 91). Several studies (including Milek and Roberts 2013 – Fig. 3.2) have used point data to reflect and detect patterns in the distribution of artefacts and micro-residues (Entwistle et al. 1998, 2000b, 2007; Milek 2012a). In most instances this is because a floor or occupation deposit contains multiple contexts or boundaries which cannot be graphically represented by surface contours based on data interpolation (Milek and Roberts 2013: 1851 – though see Negre et al. 2016). It also benefits the non-experienced reader by providing a quick and accessible understanding of each individual variable. However, point data becomes increasingly difficult to interpret visually as the number of variables and distribution maps increase. It is also likely that this type of comparative analysis misses smaller or more nuanced activity areas, particularly when structures are sampled on larger grid squares (e.g. above 1 m^2). An increasingly popular approach is the use of multivariate statistics to analyse large datasets, with principal component analysis (PCA) being the most commonly used technique (Liritzis and Zacharias 2011: 118). PCA transforms complex datasets containing multiple variables into new datasets defined by principal components (PCs) that each explain a percentage of the variance (Baxter 2016: 49–60; Jolliffe and Cadima 2016). These principal components are used to identify patterns in the data and relationships between variables and have been successfully applied to a range of geoarchaeological investigations (Jones et al. 2010; Golding et al. 2015; Mikołajczyk and Milek 2016; Mikołajczyk and Schofield 2016; Gardner 2018; Harrault et al. 2019). Another widely used algorithm is k-means clustering, which separates data points into groups based on their degree of similarity (Araujo and Marcelino 2003; Balsam et al. 2007; Baxter 2016: 63–77; Gardner 2018; Maddison and Schmidt 2020; McAdams et al. 2020).

The most significant difference between the two case studies outlined above and the Pictish sites in eastern Scotland is the survival and clarity of their occupation deposits. Twenty-five distinct floor layers were readily identified in the field during excavation of the Icelandic longhouse (Milek and Roberts 2013: 1846–1847), and even though the structure at Bornais had been extensively robbed of its structural elements and had commingled occupation deposits, micromorphology revealed them to be well-preserved, with clear evidence of depositional and post-depositional events. It was therefore hypothesised that the Pictish sites were also likely to retain hidden detail of their depositional histories and that micromorphology would be the key method utilised in their recovery. The use of integrated geoarchaeological methods also has the potential to improve the understanding of why preservation was seemingly so poor and provide additional detail regarding site activities. Neither of the two studies discussed above explored their trends through multivariate analysis, and so it was decided to evaluate how well this complemented high-resolution integrated geoarchaeology. The result was the application of integrated micromorphological, geochemical, and geomagnetic methods, together with multi-variate quantitative analyses, to the case study investigations of the Pictish settlement sites at Lair, Burghead, and Dunnicaer. Their procedures and results can be found in Chapters 6 and 7.

Each of the papers that form the core of this thesis (Chapters 4–7) contain a summary of the methods employed. However, the condensed nature of journal articles often precludes more detailed methodological descriptions or explanations of their scope. The subsequent sections are therefore intended to provide an overview of the applications and principles of the techniques applied in this thesis, alongside the specific methodological protocols followed.

3.2. Systematic literature analysis

Literature analysis as a research method involves the systematic collection and synthesis of results from primary qualitative studies (Baumeister and Leary 1997; Tranfield et al. 2003; Snyder 2019). Its purpose is to create a foundation for advancing knowledge by highlighting gaps or discrepancies in the literature, exposing unresolved issues, and facilitating the development of future research questions (Torraco 2005: 358–359; Imel 2011: 145; Turner 2018: 113; Snyder 2019: 333). The different methods and approaches to literature analysis have been discussed at length elsewhere (see Cooper 2003; Torraco 2005; Onwuegbuzie et al. 2012), however two main points are particularly relevant to the methodology employed in this thesis. First, there is debate over whether literature analysis needs to be exhaustive (Bruce 2001; Boote and Beile 2005; Seers 2015: 36; Turner 2018). Turner (2018: 114) observes that exhaustive coverage is rarely achieved in publications, partially due to space considerations, but that 'representative coverage' reviews can provide sufficient levels of detail so long as the researcher makes clear the enforced parameters (following Cooper 2003). Second, the empirical and/or qualitative results of primary studies should not be viewed in isolation. Onwuegbuzie et al. (2012: 5) have highlighted the need to analyse work as a whole in order to adequately contextualise the findings and drew specific emphasis to issues such as sample size, sampling schemes, and analytical techniques.

As the primary aim of this thesis was to identify the site formation processes which created, modified, and continue to affect archaeological sites in eastern Scotland, a broad literature review of potential post-depositional processes was conducted prior to commencing any site-based or regional analyses. The intention was to provide a reference collection of possible impacts and included, where possible, the identification of Scottish studies and examples as evidence of their impact within comparative environmental settings. This has been included as Appendix 1.

For Paper 1 (Chapter 4; Reid and Milek 2021), literature analysis was conducted to provide a catalogue of the post-depositional processes impacting early medieval remains across eastern Scotland. Sites were selected for analysis if they contained settlement features (e.g. structures, hearths, pits) radiocarbon dated to the Pictish period (spanning approximately AD 300–1000). As this was intended to be a non-exhaustive literature analysis (following Turner 2018: 114), a time frame of the last 30 years was employed to limit the number of sites (thus permitting a more detailed discussion) and encourage a review of more recently excavated sites. This included the vast majority of Pictish settlement evidence for the area and was deemed to provide suitable 'representative coverage'. Published and unpublished excavation reports were read thoroughly to identify a variety of preservation conditions and post-depositional processes. Longer texts (e.g. monographs) were subjected to semi-automated word searches to identify passages with information on preservation. Search terms comprised full and partial words that related to the analysis and identification of site formation processes; for example, searching for 'sampl' could produce results for sampling, sample, samples and sampled (Appendix 2). The presence/absence of observed processes was recorded in a Microsoft Excel database, alongside notes on their nature, extent, impact, and any method of analysis that aided their identification.

3.2.1. Comparison with national datasets

National datasets related to the processes identified in the literature were selected for comparison with site-based observations. This included the Land Cover Map 2015 (LCM2015 – Rowland et al. 2017), the Coastal Erosion Susceptibility Model (CESM – Fitton et al. 2016a, 2016b) and the Dynamic Coast National Coastal Change Assessment – Dynamic Coast 2020). The online version of the CESM was not functional at the time of writing Paper 1, so data was requested and transferred directly from the author, Dr James Fitton (University College Cork). In the absence of a subsoil pH map, the Soils of Scotland Topsoil pH dataset (James Hutton Institute 2012) was used to assess whether this acted as a suitable proxy for sediment acidity. As there is currently no national or UK-based dataset relating to soil turnover, earthworm/macrofauna density, or redox conditions, it was not possible to assess bioturbation levels or oxic/anoxic preservation conditions.

Soil properties were also recorded to assess whether national soil data offered a useful means of estimating preservation environments in archaeological sites. For example, poorly drained sites can result in waterlogged conditions favourable to the preservation of organic remains. The Soil Information for Scottish Soils (SIFSS – recently renamed SoilFinder Scotland) website is an online interactive platform that divides the country into numbered soil mapping units known as QMUNITs (James Hutton Institute 2020). Each QMUNIT identifies a unique combination of parent material, landforms and component soil types, and relates this to information on soil colour, structure, drainage and chemical properties. Different soil types are categorised into taxonomic units known as ‘series’, which are grouped under an ‘association’ based on their parent material. These soil series relay information on drainage conditions and chemical properties that can affect the waterlogging, leaching or acidity of archaeological deposits.

Values and information for each site were collected by importing the LCM2015, CESM and Soils of Scotland Topsoil pH datasets into QGIS 3.14.1 as shapefiles, plotting the locations of settlement evidence (using NGRs reported in Historic Environment Scotland’s Canmore database) and extracting data using the Point Sampling Tool plug-in. Data from the NCCA (Dynamic Coast 2020) and SIFSS (James Hutton Institute 2020) were collected directly from their online mapping services. Sites located in the coastal zone were limited to just two examples (Burghead and Dunnicaer) and were recorded separately. The degree to which national data corresponded with site-based observations was assessed qualitatively and ranked on a scale using the categories “Very Similar”, “Similar”, “Neutral”, “Dissimilar” and “Very Dissimilar”. Where the national datasets returned no value for the entered NGR, it was assigned the category “No Data”. The ranking criterion used to compare each of datasets can be viewed in Appendix 2.

3.3. On-site sampling

The geoarchaeological sampling strategy employed at each of the case study sites involved the collection of bulk samples from a 0.5 m grid across assumed floor deposits, and micromorphological samples from targeted stratigraphic sequences. This approach ensured that data was captured both vertically and horizontally, permitting a high-resolution, three-dimensional understanding of the study areas. Excavations were principally conducted in accordance with the project aims of the Perth and Kinross Heritage Trust (Lair) and the University of Aberdeen’s *Northern Picts* project (Dunnicaer and Burghead). Significant areas were opened across archaeological deposits (known from previous evaluation trenches) to aid the identification of internal stratification, structural and artefactual material, evidence of damage from post-depositional processes, and wider phasing across the sites. Geoarchaeological investigation was considered prior to each excavation and included in the planning, aims and sampling strategies for each site. Once deposits suitable for geoarchaeological investigation were identified, areas were cleaned, drawn at 1:20 (plan) or

1:10 (section) scale, and photographed according to the Chartered Institute for Archaeologists' (CIfA) Code of Practice (CIfA 2014).

3.3.1. Bulk sampling

Each site was sampled using a 0.5 m grid to provide high resolution mapping and analysis of the archaeological surfaces (Fig. 3.3). Small bulk samples (c. 200 ml) for geochemical analysis were collected using a clean trowel for each grid square, deposited into clean plastic bags, and labelled with the corresponding grid number and/or sample number. Large bulk samples (c. 2 L) for each grid square were also collected for Lair but were not assessed for this study. They are currently stored at Durham University.

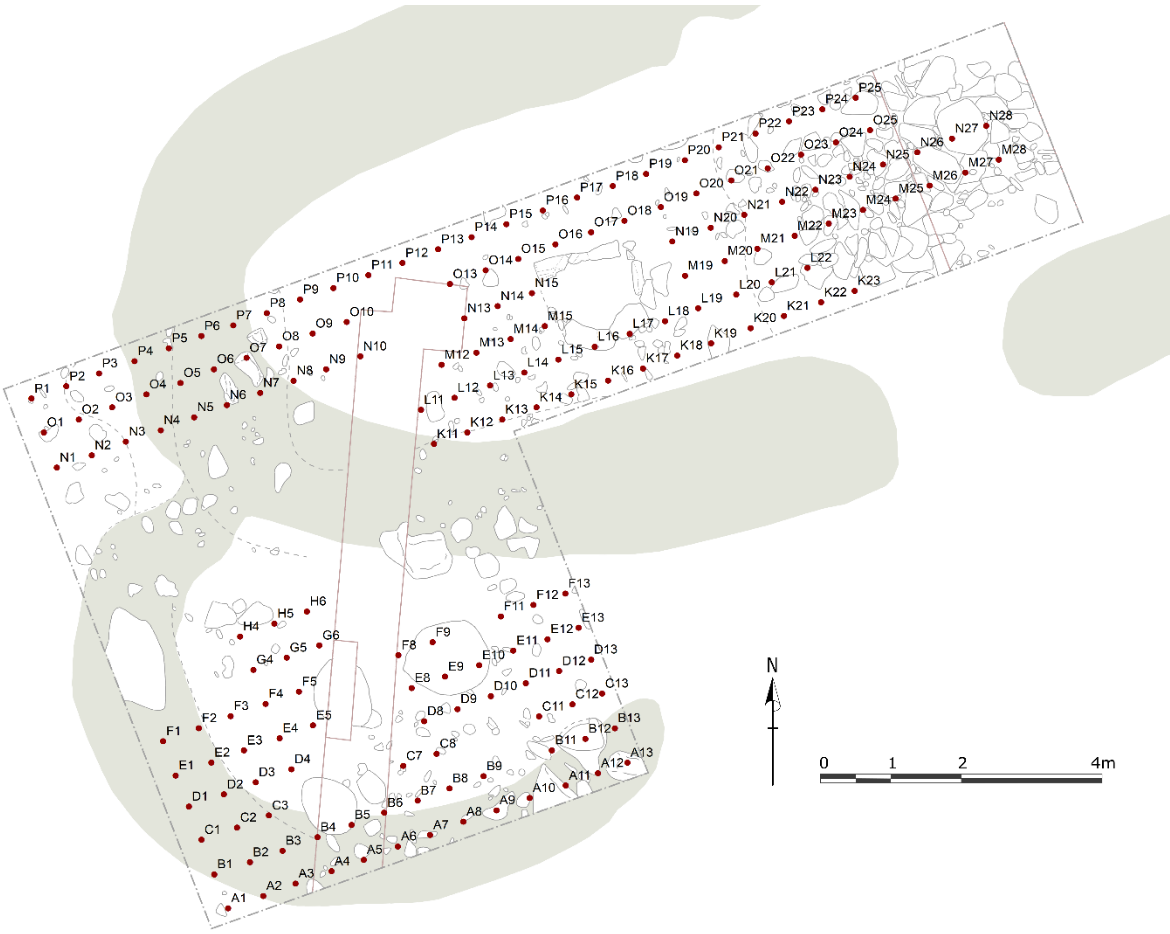

Fig. 3.3. Sample locations and grid numbers used at Lair as example of 0.5 m systematic grid strategy for bulk sampling

3.3.2. Control sampling

There is considerable debate as to whether control samples are a fundamental requirement of site-based geoarchaeological assessments. The purpose of control sampling is to determine the non-anthropogenic or background level of natural soils against which site-based enhancements can be compared. Control samples are taken 'off-site' (away from the area of archaeological interest) in a location with similar characteristics to the study site and must be collected and analysed in exactly the same manner as on-site deposits (Kolb 2016: 15). Many researchers believe controls to be an essential part of geochemical evaluations (Holliday and Stein 1989; Entwistle et al. 1998, 2000a, 2000b, 2007; Knudson et al. 2004; Guttmann et al. 2006), however others have raised concern over the extent to which controls are actually fit for purpose (Oonk 2009: 43). The main issue lies in identifying deposits that have not been affected by human activity. This is most commonly encountered in modern urban centres or agricultural landscapes, however even rural locations above the altitudinal limits of intensive cultivation are likely to have been subjected to anthropogenic and animal activity for several thousand years (Kolb 2016: 15).

Suitable controls were not sourced at any of the case study sites, owing to their location in a town (Burghead), agricultural landscape (Dunnicaer) and multi-period settlement (Lair). An alternative approach applied in this thesis was to solely examine internal patterning and interpret sites with regard to intrasite variability, rather than absolute values (following Milek and Roberts 2013). It should also be stressed that the values obtained through geochemical and multi-element analysis cannot be directly compared across different sites, even when suitable controls have been sourced (Bintliff et al. 2022: 1).

3.3.3. Micromorphological sampling

The aim of micromorphological sampling is to obtain undisturbed blocks of sediment that can be thin sectioned and analysed on petrographic microscopes to allow for the study of how archaeological material was deposited and how this record had been altered by chemical, physical and biological processes. The micromorphology sampling strategy employed in this thesis was judgment-based and designed to investigate specific aspects of archaeological deposits, such as visible (*i*) and non-visible (*ii*) stratigraphy, use of space (*iii*) and post-depositional processes (*iv*). The following principles were followed:

i. Visible stratigraphy was targeted in order to understand the character of internal deposits and reconstruct depositional histories.

ii. Areas with non-visible strata were also targeted to achieve a broad assessment of depositional histories and post-depositional processes. A lack of coherent stratigraphy is a common issue encountered on early medieval settlement sites and understanding the reasons behind this, and assessing the value and contribution of micromorphological analysis, were key objectives of the study.

iii. Where physical features indicated a partitioned use of space within a structure (e.g. the paved byre at Lair), samples were collected from these areas. This was intended to assess whether micromorphology could detect any differences in depositional practices and whether these signatures could provide clues as to the lack of stratigraphy observed more generally.

iv. Targeted sampling of areas with clear post-depositional events was also conducted, with the aim of investigating site-specific events such as burning and reuse. A broader assessment of post-depositional processes (bioturbation, leaching etc.) was planned for all samples and thus sampling solely for the investigation of these processes was not required.

Once targeted sections were identified, samples were collected by pressing aluminium Kubiëna tins (80 mm x 60 mm x 40 mm or 100 mm x 95 mm x 57 mm) into the desired section until filled. The tins were then photographed *in situ* and their location recorded on the relevant section drawing, before being cut out of the profile using a sharp trowel. Once removed, each tin was labelled with the site code, sample number and an arrow showing the direction of the top of the sample. Samples were then securely wrapped in cling film and duct tape, relabelled, and stored in a plastic container lined with bubble-wrap for transport.

3.4. Laboratory techniques and protocols

3.4.1. Bulk sample preparation

Preparation of the bulk samples was conducted at the Environmental Processing Laboratory, Department of Archaeology, Durham University. Bulk samples were air-dried, gently powdered with a mortar and pestle, and sieved through a 2 mm mesh. The fraction below 2 mm was used for sedimentary analyses, while the fraction above 2 mm was sorted by hand and examined for microrefuse. Any microartefacts, such as charcoal and burnt bone, were then counted. As bulk volumes varied, the volume of each sample was recorded prior to sieving (V_{bulk}) and used to calculate a standardised value of microartefacts (S_{MA}) for a 200 ml sample using the formula below:

$$S_{MA} = \frac{n}{V_{bulk}} \times 200$$

3.4.2. Soil pH and electrical conductivity

The pH of a soil solution is a determination of relative acidity/alkalinity based on the concentration of hydrogen ions in a soil or sediment. The pH scale ranges from 1 (most acidic) to 14 (most basic), with 7 being neutral, and is a short form for the negative base 10 logarithm of the H^+ ions (e.g. pH = $-\log_{10}[H^+]$). Archaeological applications of soil pH typically involve the identification of soil conditions which may have impacted the preservation of certain artefacts and environmental evidence (Kibblewhite et al. 2015). Soil pH can also be used to understand processes that affect soil dynamics and the survival of diagnostic features within soil profiles, such as calcitic or carbonate sediment components (Milek and French 2007: 324–325; Canti 2017: 47; Canti and Brochier 2017a, 2017b). Variations in pH also affect the bioavailability of certain elements, as well as their vulnerability to leaching, and thus soil acidity/alkalinity is an important consideration for multi-element analysis (Entwistle et al. 1998: 63; Wilson et al. 2008).

Electrical conductivity (EC) is a measure of how well a substance can conduct an electrical current and is often used as a proxy measurement for the concentration of soluble salts (ions) in a soil or sediment (Milek and Roberts 2013: 1846). Materials high in soluble salts include urine, sea salt and seaweed, making EC a useful method for site activity area analysis when samples are taken systematically on a grid (Milek and Roberts 2013: 1861, 1863; Seitsonen and Égüez 2021). EC on its own is not capable of determining which soluble salt is present but can be combined with multi-element analysis to identify correlations and hypothesise inputs.

Soil pH and electrical conductivity analysis were conducted in tandem at the Archaeological Science Laboratory, Department of Archaeology, Durham University. 20 ml of deionised water was added to 10 ml of prepared bulk sample and stirred using a glass rod for 2 minutes, before being left to settle for 15 minutes. Soil pH and EC were tested using a Hanna Instruments HI98130 Combo meter immersed in the soil suspension. The meter was calibrated at the start of each session using the Hanna Instruments pH Buffer Solution Kit (HI-77400C) and the Hanna Instruments Conductivity Standard Solution (HI-70031C). The meter's probe was rinsed in deionised water before each measurement to prevent contamination.

3.4.3. Loss-on-ignition

Loss-on-ignition (LOI) is a method of estimating how much organic matter a soil or sediment contains. At an ignition temperature of 550°C, organic matter is oxidised to carbon dioxide and ash; the weight percent lost is a proxy measurement of organic matter content (Heiri et al. 2001). Sources of organic matter include all plant and animal tissues, from fresh to decomposed, which become enhanced in settlement areas through human and animal activity. Loss-on-ignition is therefore used to distinguish sediment composition and identify activity areas such as middens, cooking pits, animal pens, and areas involved in the use/disposal of organic building materials such as turf (Entwistle et al. 2000b; Milek and Roberts 2013; Gustavsen et al. 2018; Wilken et al. 2022). Different organic inputs can be interpreted based on their elemental signatures, and certain elements (e.g. Cu, Ni, Nd) are retained in soils by adsorption to organic matter; thus, loss-on-ignition is often used as an aid to multi-element analysis (Kabata-Pendias 2010: 76; Enwhistle et al. 2000b: 297). Loss-on-ignition can also provide quantitative support to micromorphological estimations (Zhuang et al. 2013).

Estimation of organic matter content (OM) by loss-on-ignition was conducted at the Archaeological Science Laboratory, Department of Archaeology, Durham University.

Approximately 10g of prepared bulk sample was transferred to a crucible of known weight and dried in an oven for three hours at 105˚C, before being immediately transferred to an analytical balance pan to obtain the dry weight of the sample. After weighing, the sample was heated for a further three hours at 550°C and re-weighed once it had cooled to 105°C. When samples were heated in batches and could not be weighed immediately, they were transferred to a desiccator to prevent any rehydration of the sediment. A proxy measurement for organic matter content was then calculated using the formula below:

$$\%OM = \frac{dry\ weight\ (105°C) -\ post\text{-}\ ignition\ weight\ (550°C)}{dry\ weight\ (105°C)} \times 100$$

3.4.4. Magnetic susceptibility

Magnetic susceptibility determines the degree to which a soil or sediment is magnetic. The magnetic characteristics of a soil or sediment can be influenced by natural factors, such as soil development processes, but the effects of human activities are much more profound. High temperatures cause iron in the soil to be converted to magnetite and enhanced magnetic susceptibility values in archaeological sediments can therefore be used as indicators of burnt soil particles and peat/turf ash (Tite and Mullins 1971; Jones et al. 2010: 35; Nesbitt et al. 2013: 14). The technique has commonly been used to identify hearths (Gustavsen et al. 2018), differentiate fuel sources (Peters et al. 2004), and recognise maintenance practices such as the spreading of ash (Nesbitt et al. 2013: 14). Soils and sediments which contain iron hammerscale will also show elevated magnetism (Bayley et al. 2001).

Magnetic susceptibility analysis was conducted at the Environmental Archaeology Laboratory, Department of Archaeology, Durham University. 10cm^3 plastic pots were filled with the prepared bulk samples and weighed to obtain the bulk density. Magnetic susceptibility measurements were calibrated against the earth's ambient magnetism and taken in triplicate using a Bartington Instruments MS3 magnetic susceptibility meter attached to an MS2B dual frequency sensor using the low frequency setting (following Dearing 1999). The average value of the three measurements was divided by the bulk density of the sample to give the mass-specific susceptibility.

3.4.5. Multi-element analysis by pXRF

X-ray fluorescence (XRF) is a method of relative elemental characterisation commonly applied to archaeological soils and sediments. Portable XRF (pXRF) is the miniaturisation of this technology into a hand-held instrument, which can be used for *in situ* analysis or conventional laboratory preparations (Potts and West 2009). The principle of operation involves irradiating samples with photons from an X-ray tube or radioisotopic source, which excite electrons in the sample (Arai 2006; Shackley 2016: 1026). This results in the emission of secondary ('fluorescent') x-rays that occur at energies specific to different elements (Shackley 2016: 1026). Emissions are translated to peaks over a given energy spectrum and the height or intensity of a peak is used to calculate the relative concentration of an element in the sample (Shackley 2016: 1026). PXRF is a powerful technique but is incapable of exciting elements with low atomic numbers, making the determination of elements below magnesium (Mg) on the period table problematic (Potts and West 2009). Elements with a lower atomic number than this (e.g. hydrogen (H), oxygen (O), nitrogen (N), carbon (C)) often comprise much of the chemical component of a soil or sediment and thus readings do not constitute 100% of the total weight of the sample.

The elemental signatures of soil and sediments reflect an immeasurable catalogue of inorganic and organic inputs. Soils develop through the simultaneous weathering of geological parent material and the decay of plant and animal residues on their surface; they are also impacted by erosion, drainage conditions and changing hydrological regimes that can mobilise or stabilise certain portions of the elemental system (Wilson et al. 2008: 413; Holliday et al. 2016; Berhe et al. 2018). Human activities, such as construction, animal keeping, agricultural regimes, waste disposal, and resource gathering for food, fuel and crafts, add different element enrichments to these signatures (see Haslam and Tibbett 2004; Oonk et al. 2009; Bintliff and Degryse 2022b). Once material has been deposited, these assemblages are further subjected to the wide range of natural and anthropogenic processes that affect total soil element concentrations (Haslam and Tibbett 2004; Wilson et al. 2008). It is impossible to account for all depositional and post-depositional processes that have affected an archaeological assemblage and interpreting elemental signatures is therefore complex and inexact. The best attempts establish an awareness of possible impacts (see Appendix 1) and utilise corroborating techniques, such as microrefuse analysis, micromorphology, LOI and pH (e.g. Jones et al. 2010; Milek 2012a; Milek and Roberts 2013), as well as the results of experimental and ethnographic research (e.g. Knudson et al. 2004; Macphail et al. 2004; Terry et al. 2004; Goldberg and Macphail 2006: 247–267). Numerous findings have demonstrated that no single element is indicative of a single archaeological process, and many have both organic and inorganic sources. Nevertheless, studies generally divide elements into those more indicative of anthropogenic activity (e.g. Ba, Ca, Cu, Mn, P, Pb, Sr, Zn.), and those more related to geological sources and pedogenic processes (e.g. Al, Cr, Fe, Rb, Si, Ti, V, Zr) (Gardner 2019: 48; see Oonk et al. 2009; Vyncke et al. 2011; Dirix et al. 2013; Neilsen and Kristiansen 2014; Mikołajczyk and Milek 2016; Bintliff and Degryse 2022b).

Multi-element analysis by portable x-ray fluorescence (pXRF) was conducted at the OSL and XRF Laboratory, Department of Biological and Environmental Sciences, University of Stirling. Element concentration determination was performed using a bench-mounted portable NITON XL3t-Goldd+ Thermo Scientific X-ray fluorescence analyser. For each sample, a sediment pellet was prepared by pressing approximately 5g of the prepared bulk sample to a pressure of 11 Tons using a Perkin-Elmer press. Pellets with a depth of 10 mm were placed on the surface of the detector before activating the device. The equipment was operated in Cu/Zn mining mode and the instrument was configured to run for 60 seconds per sample with four sequential settings: main (15 s), low (10 s), high (10 s) and light (25 s). Using proprietary software, elemental concentrations were calculated using a theoretical calibration model (Hf/Ta) from the resultant spectra. Five replicate measurements were taken for each pellet (three on one side and two on the reverse) and the mean value was accepted as representative of the grid square.

Spectra and values obtained from the XL3t (in %) were downloaded for analysis on the Thermo Scientific Niton Data Transfer (NDT) PC software suite. Values were also downloaded into Microsoft Excel, which permitted a calculation of the mean for each sample. Elements which did not report values within the limit of detection (LOD) or reported very infrequently with randomised patterning (assessed via spatial distribution mapping – see 3.7) were removed from the datasets. Where elements returned partial values within the limit of detection and displayed non-randomised patterning (e.g. Burghead, Chapter 7), grid squares with element concentrations below the limit of detection (< LOD) were substituted with LOD/2 in accordance with Farnham et al. (2002). Detailed results have been supplied in Supplementary Materials that will be published online alongside their associated research paper. They have also been provided at the end of this document in Appendix 2.

3.5. Micromorphology

Micromorphology involves the examination of thin-sectioned soils and sediments under a polarising light microscope. This facilitates the identification and quantification of soil structure, texture and mineralogy, which are used to differentiate stratigraphic units, provide information on depositional events, and recognise processes such as compaction and trampling (e.g. Milek 2012a, 2012b; Banerjea et al. 2015; Huisman and Milek 2017; Rentzel et al. 2017). Inclusions that help reconstruct site activities, such as bone, shell, charcoal, phytoliths, diatoms, ash residues, and plant remains can also be studied in thin section (see Nicosia and Stoops 2017). This permits an examination of their occurrence *in situ* and aids the interpretation of macroartefact recovery. It is also possible to observe the activity of soil fauna and roots, and the presence of iron, manganese, and calcium carbonate, which can clarify drainage conditions and post-depositional processes such as bioturbation and leaching.

In much the same way as the elemental signatures mentioned above (section 3.4), the physical characteristics of thin-sections reflect a palimpsest of natural and anthropogenic processes. Inclusions can be formed *in situ* or deposited by human, animal, or geological activity. Micromorphologists therefore need to be aware of the local geology and topography of individual sites, alongside knowledge of how soils and sediments can form and change across time and under different environmental conditions (Gardner 2018: 45). The analysis of soil and sediment thin sections is complex and subjective, and relies heavily on the experience and awareness of the micromorphologist. No two thin section will ever look the same and though several guidelines exist for the description and quantification stages of analysis (e.g. Bullock et al. 1985; Stoops 2021), establishing a model of interpretation is impossible. The best interpretations are therefore made with an appreciation of possible depositional and post-depositional impacts (included in Appendix 1) and utilise a wide range of reference materials.

3.5.1. Preparation

Micromorphology samples from the sites of Lair and Burghead were manufactured at the Thin Section Slide Production Laboratory, Department of Biological and Environmental Sciences, University of Stirling, by George MacLeod and prepared following the Thin Section Micromorphology Laboratory’s standard procedures (University of Stirling 2008). The samples from Dunnicaer were manufactured by the author of this thesis at the same facility under the supervision and training of George MacLeod. The method and duration of drying was determined by the moisture content of the samples; samples from Lair and Dunnicaer were rich in organic matter and were dried using a vapour phase acetone exchange, whilst the sandier Burghead samples required only air-drying. Once dried, samples were impregnated with crystic polyester resin (Polylite 32032-00 resin with a methyl-ethyl-ketone-peroxide (MEKP) catalyst) and placed under vacuum overnight, before being left to cure for several months. Slices of the impregnated block were cut to approximately 1 cm thick using a Buehler Petrocut abrasive cutter, before being ground on a lapping plate (Logitech LP40/50) using 15 μm calcined aluminium oxide in water. The sample slice was then bonded to a glass slide using 301 epoxy resin. Excess material was cut off using the abrasive cutter before being precision lapped to 30 μm. Thin-sections were polished on a Preciso CL-40 polishing machine with 3 μm diamond in oil suspension, before being cleaned to remove any residual oil and finally cover-slipped.

3.5.2. Microscopy

Microscopic analysis of the thin-sections was performed at the Microscopy Laboratory, Department of Archaeology, Durham University. Initial assessment of the thin-sections was conducted at a 1:1 scale on a lightbox to identify primary microstratigraphic units and any obvious features such as large channels or inclusions. Microscopic observations were made using Leica M80 and Leica DM2700 P microscopes at a range of magnifications from x4 to x400 with plane-polarised light (PPL), oblique incident light (OIL) and cross-polarised light (XPL). Thin-section description was conducted using the identification and quantification criteria set out by Bullock et al. (1985) and Stoops (2021). The interpretation of thin-sections was aided by reference to experimental and ethnoarchaeological material held at Durham University, published reference guides including Nicosia and Stoops (2017), Macphail and Goldberg (2018), Stoops et al. (2018) and Fitzpatrick (1984), and the experience of Professor Karen Milek, primary supervisor of this thesis. This process produced a range of qualitative and semi-quantitative data that was displayed in summary tables in Chapters 6 and 7. Further details are contained in their associated Supplementary Materials, provided in this thesis as Appendix 2).

3.6. Statistical methodology

3.6.1. Data exploration and statistical tests

Initial exploration of quantitative data was conducted in IBM SPSS. This included basic descriptive statistics (measures of frequency, tendency and variation) and box-and-whisker plots to explore the data non-parametrically and identify outliers. As normal data is an underlying assumption in parametric testing, normality was assessed both graphically and statistically. Statistical tests have the advantage of making an objective judgment of normality; Kolmogorov-Smirnov tests were used to indicate normality in larger sample sets ($n \geq 50$) and Shapiro-Wilk tests used for smaller sample sets ($n < 50$). Both operate on the premise that when $p > 0.05$, the null hypothesis is accepted, and data are deemed to be normally distributed (Mishra et al. 2019: 70). Of the 87 variables assessed across four datasets, 65 (74.7%) failed statistical normality tests. However, central limit theorem states that in a sufficiently large sample size ($n \geq 30$), distribution of a variable's mean will be approximately normal regardless of that variable's distribution in the population (Kwak and Kim 2017; Kamis and Lynch 2020). Thus, violation of the normality is unlikely to affect further statistical investigation. A summary of how this has been applied in this thesis is provided in Table 3.1.

Table 3.1. Summary of normality tests and assumed normality applied to datatsets

Dataset	Sample size (n)	Test of normality	Central limit theorem
Lair	180	Kolmogorov–Smirnov	Yes
Burghead upper	96	Kolmogorov–Smirnov	Yes
Burghead lower	131	Kolmogorov–Smirnov	Yes
Dunnicaer	24	Shapiro-Wilk	No

3.6.2. Data analysis

The geochemical, geomagnetic and multi-element datasets were combined and interrogated using principal component analysis (PCA) to reduce their dimensionality and increase interpretability (Jolliffe and Cadima 2016: 1). Outliers were included in the data analysis as they were deemed to exhibit variability of the sediments assessed (following Gardner 2018).

The exception to this was the Lair dataset, where one sample (n=160; grid square P5) contained maximum or minimum values for 11 of the 20 variables and significantly skewed results. The location of P5 within a turf wall did not provide a sufficient explanation for this variance and it is likely that these results indicate contamination or a highly localised post-depositional process, such as an animal burrow. The decision was therefore made to remove grid point P5 from further statistical investigation. Microrefuse and elements whose <LOD values exceeded 25% of the replicates were also excluded from statistical investigation (in accordance with Farnham et al. 2002). As the variables were measured in different scales, standardisation (z-score) was performed prior to PCA to ensure that each variable contributed equally.

Kaiser-Meyer-Olkin (KMO) tests for sampling adequacy indicated that three of the four standardised datasets were suitable for principal component analysis (PCA). This statistic reflects the proportion of variance among variables that might be caused by an underlying factor; the higher the value, the more suitable the data is for PCA (Shrestha 2021: 6). In general, KMO values between 0.8 and 1 indicate that sampling is adequate; KMO values less than 0.5 indicate the sampling is not adequate and PCA results are not suitable for examination of the data (Shrestha 2021: 6). The value returned for the Dunnicaer dataset lay well below the acceptable KMO statistic (Table 3.2) and was deemed to be the result of small sample size. The minimum sample size required for PCA has been debated widely (see Shaukat et al. 2016: 176 – 177); Gorsuch (1983) recommends at least 100 samples, whereas Hatcher (1994) and Bryant and Yarnold (1995) suggest that sample size should be at least five times larger than the number of variables. Others have argued for sample sizes in excess of 150 (Comrey and Lee 1992: 217; Tabachnick and Fiddell 2019: 481–482). The sample size for Dunnicaer (n = 24) did not fulfil any of these criteria and thus PCA was not performed on this dataset.

Table 3.2. KMO statistics and suitability for PCA

Dataset	KMO result	Pass/fail	PCA
Lair	0.82	Pass	Yes
Burghead upper	0.89	Pass	Yes
Burghead lower	0.87	Pass	Yes
Dunnicaer	0.33	Fail	No

Principal component analysis (PCA) was applied to the three remaining datasets to examine the overall structure of the data. This was conducted using both IBM SPSS and OriginLab Origin Pro, as the latter permitted the creation of data biplots. Pearson's correlation tables were established as part of the PCA statistical outputs for Lair and Burghead to assess the strength and direction of linear relationships between pairs of variables. An additional correlation table was established for the Dunnicaer dataset, though this was Spearman's rather than Pearson's, as the former is more suited to non-parametric data.

Following PCA, the Lair dataset was subjected to *k*-means clustering to assess whether the data could be meaningfully separated into a predetermined number of groups. *K*-means clustering is an unsupervised learning method that identifies *k* number of centroids and allocates each data point to the nearest cluster (Sinaga and Yang 2020). The hypothesis was that these clusters would relate to areas of the structure with known differences in use and/or composition (e.g. living areas, animal areas, annexe, turf walls). The number of clusters applied to the Lair dataset ($k = 4$) was determined by hierarchical clustering analysis, interpreted through dendrograms (Appendix 2).

3.7. Distribution maps

PCA results were interpolated by ordinary kriging in ArcMap 10.8.2 to provide a more visual representation of the data. Interpolated surfaces were compared against distribution maps of the geochemical, magnetic and multi-element point data to corroborate results and inform interpretations. Distribution maps of *k*-means clusters, microrefuse and elements excluded from statistical analysis (Cl, Cu, Ni, Pb, V, Zn) were also generated. Graduated symbols in equal intervals were chosen to represent the individual variables, as interpolation was not possible between different contexts and across walls (following Milek and Roberts 2013: 1851). The exception to this rule was the Burghead upper surface, which was represented by graduated symbols in natural breaks (Jenks). Contamination in the south of the trench had elevated element concentrations to such an extent that more nuanced signatures in archaeological deposits were masked by equal interval mapping.

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The combined application of these methods in a Scottish context are unique, and the selected sampling, analytical, and data representation methods used all represent best practice. This thesis therefore provides several methodological principles and protocols that can be reproduced in archaeological investigations across Scotland and more globally. Most original to this thesis is the comparison of a semi-quantitative literature analysis with the information held in national soil and land datasets. As the archaeological use of national soil data has primarily concentrated on site prospection, its application in assessing heritage at risk offers a novel deviation from previous studies.

4. Research Paper 1

Risk and resources: An evaluation of the ability of national soil datasets to predict post-depositional processes in archaeological sites and heritage at risk

Reid, V. and Milek, K. 2021. 'Risk and resources: an evaluation of the ability of national soil datasets to predict post-depositional processes in archaeological sites and heritage at risk'. Heritage 4: 725–758.

This paper comprises a qualitative and semi-quantitative literature analysis of post-depositional processes affecting early medieval Scottish sites. It seeks to address the primary aim of this thesis (Chapter 1, section 1.3) and research question *i* (RQ *i*) by analysing the evidence for post-depositional processes reported in excavation literature. It then summarises this to form a foundational assessment of the types of processes that are being identified and recorded in the region. The paper develops this review by comparing the results against national datasets on land use, soil type and soil pH, as well as two national coastal erosion models. This permits an examination of whether these datasets are a viable means of remotely assessing post-depositional events in heritage management strategies (such as risk maps) or in cases where excavations do not have the means to conduct detailed analyses (RQ *vi*). This paper was published in the MDPI open access journal *Heritage*.

The concept of this paper was developed in partnership with co-author Karen Milek (primary supervisor to this thesis). As the first author of this paper, I was responsible for the research design, data collection, visualisation, and the interpretation of the results. I wrote the first full draft of the paper and corrected subsequent drafts based on comments by the co-author, supervisors and journal reviewers. Both authors read and agreed to the published version of the manuscript prior to final submission.

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Risk and Resources: An Evaluation of the Ability of National Soil Datasets to Predict Post-Depositional Processes in Archaeological Sites and Heritage at Risk

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Abstract: Previous studies have demonstrated the vast range of physical, chemical and biological processes that influence the preservation of archaeological sites, yet characterisation at the site-level remains largely unexplored. National datasets on soil type, land use and erosion modelling have the potential to predict localised impacts but remain an untapped resource in the evaluation of heritage at risk. Using early medieval Scotland as a case study, this paper explores in detail some of the primary factors which have impacted the archaeological record and the degree to which site-based evidence contained in excavation reports compares with national datasets (Land Cover Map 2015, Soil Information for Scottish Soils and Soils of Scotland Topsoil pH) and coastal erosion models (Dynamic Coast National Coastal Change Assessment and Coastal Erosion Susceptibility Model). This provides valuable information on the preservation of Scotland's early medieval settlement, as well as a methodology for using national datasets in the remote assessment of post-depositional factors across the broader archaeological landscape. Results indicate that agriculture, bioturbation and aggressive soil conditions are among the most significant factors impacting Scotland's archaeological remains. While the national datasets examined have the potential to inform heritage management strategies on these processes, their use is limited by a number of theoretical and methodological issues. Moving forward, site-specific studies that characterise the preservation environment will be crucial in developing baseline assessments that will advance both local and global understandings of destructive factors and soil-mediated decay.

Keywords: preservation; post-depositional processes; Scotland; early medieval; Pictish archaeology; assessment of risk; heritage management

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1. Introduction

From individual dwellings to large towns and cities, the remains of settlement provide a unique insight into the social, economic, political and ideological systems that shaped societies across the world. Settlement has been found in almost all geographic and environmental contexts, but the extent to which archaeologists can access these elements varies widely, not least because preservation and post-depositional events have played (and continue to play) a significant role in altering the settlement record. The factors involved are diverse but can include physical truncation as a result of land processes (e.g., agriculture, urban development and erosion) or biological and chemical degradation in the buried environment (e.g., microbial activity and soil acidity/alkalinity). Understanding how these processes have influenced a site following its original depositional phase is crucial in creating valid interpretations of the evidence, and whilst there are multiple theoretical and methodological tools at our disposal, relatively few studies explicitly engage in an analysis of post-depositional processes.

In opening up this conversation, this paper presents a case study in Scotland to look at the quality of the information that can be gained from past excavation literature, and how national datasets may provide meaningful information on the preservation environment, post-depositional events and prospective threats to a region's archaeological resource. To date, a handful of studies have applied national soil survey data to the archaeological record, but their focus has primarily been on site prospection [1–3] and similar efforts have not been extended to an assessment of heritage at risk. Risk maps offer a valuable resource for heritage management; however, recent iterations have concentrated on catastrophic threats, such as natural disasters [4–6], or the long-term effects of pollution, tourism, erosion or climate change [5,7,8]. By comparison, very few efforts have mapped the risk associated with buried heritage. Given that the preservation of buried archaeology is determined at the soil interface, national soil data has the potential to form the basis of heritage risk maps that focus on post-depositional processes. However, the degree to which current data corresponds with site-based evidence has not yet been established. This is the first study to qualitatively review site-based literature and national datasets in the assessment of preservation factors, and offers a methodological framework for future practice that could be adapted and applied in any country where national soil datasets are available.

2. Scotland as a Case Study

2.1. Issues with Scotland's Early Medieval Record

Scotland's diverse landscapes—its machair sands, heather uplands, coastal zones and rolling farmlands—contain significant evidence of its early medieval populations. The period, roughly defined as AD 300–900, sits on the precipice between history and prehistory, and whilst glimmers of insight have been gained from Roman, Irish and English texts, there are few native records or historical accounts that pre-date the twelfth century [9,10]. Archaeology has proven essential in developing our understanding of the period, and much information has been gained from the analysis of funerary monuments [11,12], fortified sites [13–15] and an enigmatic material culture [16,17].

However, there remain significant gaps in the knowledge that are proving difficult to overcome. Detailed information regarding daily life is almost non-existent and there are particular geographic areas, such as Argyll in the west, that have produced almost no settlement evidence for the period [18]. Moreover, there is a significant bias in favour of rural contexts. Only a very small number of early medieval structures have been found in modern suburban settings, and there is almost no evidence in modern city centres, where it is likely that later medieval and post-medieval urban development destroyed any early medieval phases [19] (p. 11).

Obliteration as a result of modern ploughing and urban development is one of the theories put forward for the general lack of early medieval settlement observed across Scotland [20]. Yet, excavation reports clearly attest to other agents, such as coastal erosion, reuse and animal activity, playing a cumulative role in the alteration and loss of archaeological detail. The extent to which post-depositional events have shaped this fragmented record remains largely unexplored and continues to limit the interpretation of site histories and wider settlement patterns. Management solutions are similarly restricted by a poor understanding of the most significant threats to the resource which, given the increasing recognition that in situ preservation is not always the most effective strategy, requires addressing [21,22]. As such, there is a clear need to explore not only the physical aspects of early medieval settlement but also the nature and agents of its survival.

2.2. Early Medieval Settlement in Scotland

Archaeological evidence of Scotland's early medieval settlement has increased dramatically in recent decades. The record, once believed to survive largely as coastal and hilltop fortifications, has now expanded to include a range of unenclosed and enclosed settlement types spread across a variety of environmental settings. This has raised exciting new questions about political and social organisation, the relationships between different site types, and the motivations behind a shift from round to rectangular house forms—all of which currently remain unanswered [23] (p. 262). However, whilst it is now possible to identify settlement and comment on regional variations in architecture and layout [20] (pp.113–140), [24], there is little to no understanding of the roles these structures played or how their wider communities operated [23] (p. 263).

A key issue has been the generally poor preservation of settlement remains of this period. The stone-built tradition that has resulted in the survival of upstanding remains on the Western and Northern Isles (e.g., the cellular structures at Cnip, Udal, Bostadh and Old Scatness—though see [25] for commentary on the lack of analysis regarding the use of space) is not widely found across the mainland, and researchers face the distinct possibility that buildings were constructed using methods that have survived very poorly in the ground [20] (p. 140). Though structures have been reported at enclosed sites, including Clatchard Craig (Fife), Rhynie (Aberdeenshire), and the promontory forts of Burghead and Portknockie (Moray), they survived only as truncated posthole outlines and failed to produce the occupation deposits required to elucidate important information regarding their status or function [26]. Unenclosed sites have proved similarly problematic, typically consisting of single or grouped domestic structures, or more ephemeral traces such as isolated hearths and activity surfaces. Even the best-preserved examples (upstanding turf structures in the Perthshire uplands) have failed to produce clear internal deposits [27,28].

The national picture is therefore one in which we are gaining an increasing number of sites but little development in our understanding of the role or interaction between settlement types. A lack of occupation deposits, coupled with poor preservation conditions (particularly the decomposition of organic material in Scotland's well-draining acidic soils), has restricted interpretations in both unenclosed and fortified settlements, and many aspects of early medieval society—its material culture, life ways and social economy—remain frustratingly elusive.

Part of the issue lies in the fact that we do not yet fully understand the mechanisms behind the absence of detail. In some cases, the reasons are clear: the destructive natures of agriculture, erosion and urban development have been well documented and their influence across Scotland is widely apparent [20,29]. Yet, there are other cases, particularly in upland environments, where such factors have not played a significant role. At these sites, interpretations of the evidence (or lack thereof) have typically centred around function, reuse or post-depositional truncation (e.g., [28] (p. 47)), but there has been little attempt to delve any deeper into the contributing factors. Such broad interpretations do little to address important social questions and risk creating a narrative based on preconceived notions and assumptions of the preservation environment, rather than confirmed findings.

2.3. *Approaching the Issue*

It has long been accepted that reliable archaeological interpretations begin with a well-preserved and well-understood assemblage [30]. The ability to ascertain patterns of deposition and states of preservation has developed greatly over the past few decades [31], yet there has been relatively little investigation into the taphonomic and post-depositional processes occurring on early medieval settlement sites across Scotland. Where exceptions do exist, they tend to be a minor part of much larger projects, and there is little understanding of how the specific aspects of settlement (e.g., building fabric, architectural style, function or longevity of use) or its environmental context (e.g., topography, soil type or biota) can influence these taphonomic signatures.

Accessing this information is the first step in addressing the absence of detail for early medieval settlement. It will permit reliable interpretations over the survival of dwellings in different contexts and aid estimations of where settlements (now lost) may once have originally stood. Equally, it will allow an understanding of patterns in the distribution, scale and severity of post-depositional processes, and an assessment of the threats that these sites face both now and in the future. This latter point is critical in ensuring that the limited cultural resource is managed effectively, and that sites most at risk of destruction (or those that currently have the best examples of preservation) are prioritised for excavation.

Given that archaeological excavation is a destructive, expensive and time-consuming venture, the ability to assess risk remotely is becoming increasingly important. Scotland has a number of national datasets and models that have the potential to provide information on the preservation environment but, to date, their use within an archaeological context has been limited and largely concentrated on coastal erosion. Examples include the Coastal Erosion Susceptibility Model (CESM), which represents the erosion susceptibility of the coastline [32], and the National Coastal Change Assessment (Dynamic Coast NCCA), which maps past shoreline changes and projects these forward to 2050 [33,34]. The NCCA identified 874 known heritage sites within potential erosion zones; however, the degree to which these models actually reflect conditions at the site-level remains largely untested. A recent small-scale case study on Sanday, Orkney, found that local-scale vegetation edge analysis (digitised from historic maps and aerial photographs) had a higher agreement with known eroding archaeological sites than either of the two national models [35].

This gap between predicted and observed data is part of a wider problem, evidenced in Historic Environment Scotland's recent publication on the threats posed by climate change [22]. Although the document outlines the potential impacts of rainfall, temperature and extreme weather events on the nation's cultural heritage, the majority of impacts are speculative and remain untested across much of the historic environment [22]. Without a baseline understanding of how sites have already been affected by chemical, physical and biological factors, it is impossible to assess the threat posed by future changes.

This study therefore aims to address these issues by developing a desk-based analysis of post-depositional processes. Using excavation literature, it begins by cataloguing the major processes recorded on excavated early medieval settlement sites in eastern Scotland to provide a foundational understanding of taphonomic and post-depositional events at the site-level. The study then examines whether free and publicly available datasets accurately reflect the preservation conditions identified during the excavation of these sites, and evaluates whether they can provide a viable means of remotely assessing archaeological sites in Scotland, before considering the global potential of the methodology.

3. Materials and Methods

3.1. Phase 1: Site-Based Analysis

Owing to the increasing number of early medieval sites identified across the north and east of Scotland [36], a study area stretching from Dornoch in the north, to Loch Tay in the east, and North East Fife in the south (~24,000 km^2), was established (Figure 1). This area encompasses a range of different preservation environments, including heather uplands, coastal zones and arable lowlands, and was deemed a suitable case study for the evaluation of the national data in Phase 2 of the Methodology.

Sites with settlement features radiocarbon dated to the first millennium AD (spanning approximately AD 300–1000) were selected for qualitative literature review in order to catalogue the post-depositional processes impacting early medieval remains. Published and unpublished excavation reports from the last three decades were thoroughly read in order to identify a variety of preservation conditions and post-depositional processes. Longer texts were subjected to semi-automated word searches in order to identify passages with information on preservation. These search terms have been provided in Supplementary Material S1. Documents analysed included academic journal articles, data structure reports, and site-based monographs. The presence/absence of a range of observed processes was recorded in a Microsoft Excel database, alongside notes on their nature, extent and impact. Information regarding the reuse of sites was also recorded.

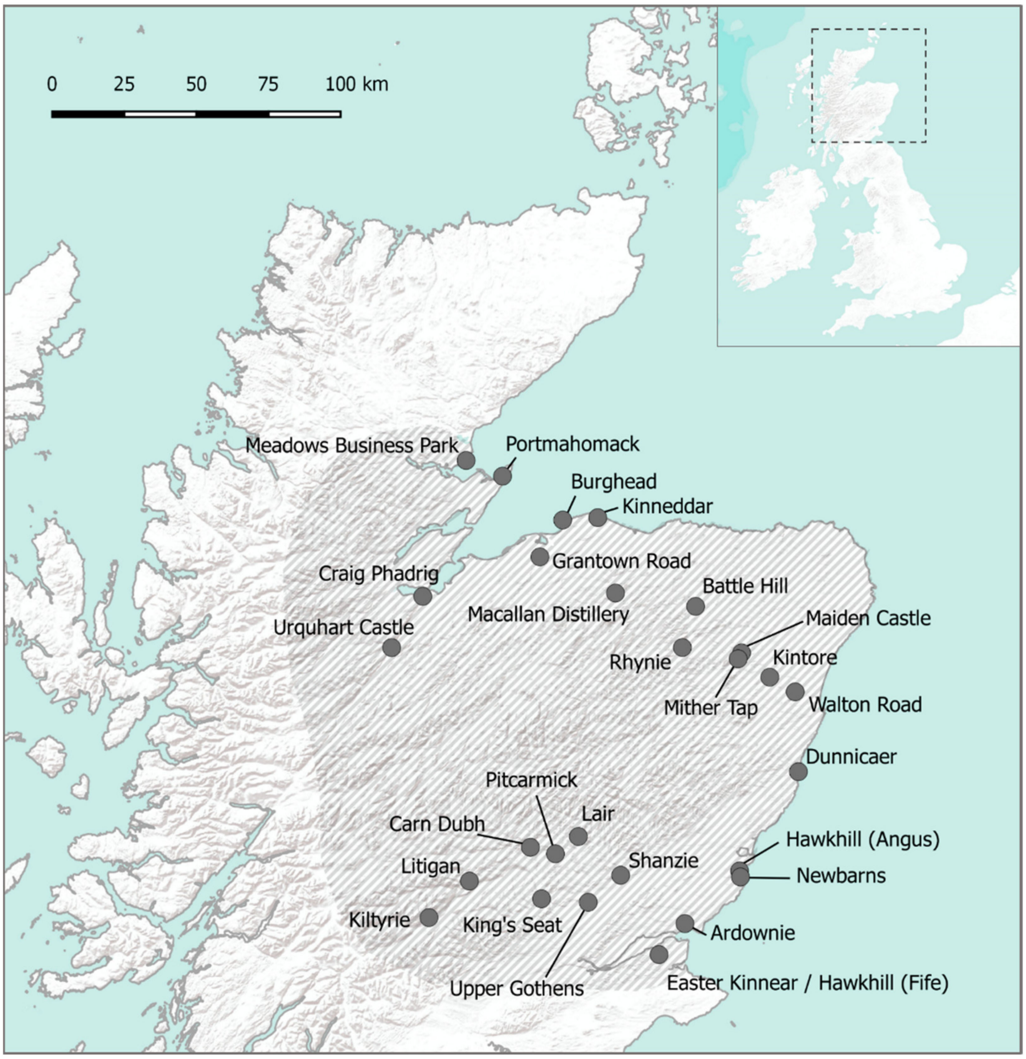

Figure 1. Locational map of Scotland (main image) in relation to UK (top right inset). Extent of study area shown as shaded area with location of sites included in catalogue [37].

A total of 65 documents were analysed in order to retrieve information regarding 27 sites with evidence of early medieval settlement activity. Settlement features at each location were grouped according to the name and identification number in Scotland's national online historic environment archive "Canmore" (canmore.org.uk).

The level of detail provided for post-depositional processes was found to vary widely depending on the nature of investigation and the type of literature available. Reports produced as a result of large-scale studies (e.g., Portmahomack and Kintore) provided the greatest detail, whilst watching briefs typically provided the least (e.g., Mither Tap). Similarly, excavations which employed specialist analysis, such as soil micromorphology, identified processes in greater detail. As such, the evidence described below should be taken as an indicator of the factors affecting early medieval settlement sites in Scotland, rather than an exhaustive catalogue. Nevertheless, a number of significant trends were identified across the literature; their occurrence at each site is summarised in Table 1 and reported in more detail in the Results section.

3.2. Phase 2: Comparison with National Data

Results from Phase 1 indicated that land use, soil acidity, erosion and bioturbation were among the primary factors impacting early medieval settlement sites. National datasets which pertained to these processes were selected for comparison with site-based observations. This included the Land Cover Map 2015 (LCM2015 [38]; available for free via the UKSO Map Viewer), the Coastal Erosion Susceptibility Model (CESM [32,39]) and the Dynamic Coast National Coastal Change Assessment [34]. In the absence of a subsoil pH map, the Soils of Scotland Topsoil pH dataset [40] was used to assess whether this acted as a suitable proxy for sediment acidity. As there is currently no national or UK-based dataset relating to soil turnover, earthworm/macrofauna density or redox conditions, an assessment of bioturbation levels or oxic/anoxic preservation conditions could not be achieved.

The soil properties reported at each site were also reviewed in order to assess whether national soil data could provide a useful means of estimating preservation environments in archaeological sites. The Soil Information for Scottish Soils (SIFSS) website is an online interactive platform that divides the country into numbered soil mapping units (QMUNITs) [41]. Each QMUNIT identifies a unique combination of parent material, landforms and component soil types, and relates this to information on soil colour, structure, drainage and chemical properties. Different soil types are categorised into taxonomic units known as 'series', which are grouped under an 'association' based on their parent material. These soil series have different drainage and chemical properties that can affect the waterlogging, leaching or acidity of archaeological deposits.

Values and information for each site were collected by importing the LCM2015, CESM and Soils of Scotland Topsoil pH datasets into QGIS 3.14.1 as shapefiles, plotting the locations of settlement evidence (using the NGRs recorded in Table 1) and extracting the data using the Point Sampling Tool plug-in. Data from the NCCA and SIFSS were both collected directly from online mapping services (Dynamic Coast and SIFSS respectively). The values for soil and land use properties are recorded in Table 2. As only two sites in the study area were located in the coastal zone, these have been recorded separately in Table 3.

The degree to which national data corresponded with the site-based observations was assessed qualitatively and ranked on a scale using the categories "Very Similar", "Similar", "Neutral", "Dissimilar" and "Very Dissimilar". Where the national datasets returned no value for the entered NGR, it was assigned the category "No Data". A ranking criterion used to compare each of datasets was established and can be viewed in Appendix A.

4. Results

4.1. Phase 1: Site-Based Analysis

The literature review identified 12 observations relating to post-depositional processes across the 27 study sites (Figure 2). The major processes have been reported in Table 1 and in greater detail below.

Table 1. Early medieval settlement evidence and primary post-depositional processes recorded in excavation literature.

Site Name	NGR	Canmore ID	Settlement Evidence (Early Medieval)	Settlement Type	Post-Depositional Processes and Observations	References
Ardownie	NO 4948 3379	68212	Hearth and paved area	Unenclosed	**Agricultural attrition** (modern ploughing); **reuse** (of Iron Age souterrain); **poor/differential preservation** (degraded bone; degraded pollen assemblage; fragmented charcoal; heather samples largely resistant to abrasion processes)	[42]
Battle Hill	NJ 54294 39943	353941	Structure; midden material	Enclosed	**Agricultural attrition** (ploughing associated with commercial woodland); **bioturbation** (disturbance by tree roots; extensive mixing by soil fauna); **reuse** (of Iron Age enclosure and area associated with Neolithic ring-mound; **reuse** in post-medieval period)	[43–45]
Burghead	NJ 1090 6914	16146	Coastal promontory fort (multiple structures; fragmented floor deposits; bone midden)	Enclosed	**Urban development** (truncation of features by 19th C. town); **coastal erosion** (active erosion at site); **reuse** (robbing of rampart material); **poor preservation** (degraded bone)	[46–49]
Carn Dubh	NN 976 605	26422	Sub-rectangular building with hearth, negative features and interior soil deposits	Unenclosed	**Agricultural attrition** (modern ploughing for afforestation); **bioturbation** (roots and invertebrates); **reuse** (of prehistoric structures and in later medieval period); **poor preservation** (of pollen assemblages); **lack of internal stratigraphy** (spread from hearth but no clear occupation horizons–reasons unclear)	[50]
Craig Phadrig	NH 6400 4527	13486	Hillfort (internal structures; palisade; ramparts)	Enclosed	**bioturbation** (tree roots–destruction of inner rampart section during storm); **reuse** (of Iron Age hillfort; reoccupation in medieval period)	[51,52]
Dunnicaer	NO 8821 8464	37001	Coastal promontory fort (multiple structures; hearths; fragmented floor deposits)	Enclosed	**Coastal erosion** (extensive loss/truncation of features including recent erosion events); **Agricultural attrition** (19th C. cultivation in upper terrace); **bioturbation** (mammals); **reuse** (remodelling in early medieval period and later 19th C. construction/robbing); **poor preservation** (highly fragmented and degraded bone–likely due to acidic soil conditions)	[53–56]

Table 1. *Cont.*

Site Name	NGR	Canmore ID	Settlement Evidence (Early Medieval)	Settlement Type	Post-Depositional Processes and Observations	References
Easter Kinnear / Hawkhill (Fife) [1]	NO 40519 23382	33257	Sub-rectangular "scooped" structures; temporary hearth; series of wattle and daub buildings	Unenclosed	**Agricultural attrition** (medieval and modern ploughing); **bioturbation** (mammals); **reuse** (of Iron Age artefacts; successive building in early medieval period); poor **preservation** (highly degraded animal bone; highly corroded metal objects; degraded stone artefacts); **lack of internal stratigraphy/features** (no floor layers in any phases at Easter Kinnear–reasons unclear; rough stone paving in Hawkhill structure but no occupation deposits or hearth)	[57]
Grantown Road	NJ 03080 57200	320363	Curvilinear structure; circular structure; isolated pits	Unenclosed	**Agricultural attrition** (modern ploughing); **slope** (site heavily slumping; infilling of negative features through soil creep, hillwash and human action); **poor/differential preservation** (highly fragmented and degraded bone; differential preservation of barley types); **lack of internal stratigraphy/features** (result of ploughing)	[58]
Hawkhill (Angus)	NO 6820 5140	35807	Metalworking features including sub-rectangular structure or "revetted" platform, paving and hearth/forge; post-setting and triple inhumation	Unenclosed	**Agricultural attrition** (medieval/post-medieval and modern ploughing); **bioturbation** (earthworms); **reuse** (of Iron Age building material); **poor/differential preservation** (highly degraded bone; poorly preserved cereal assemblage; ecofact preservation better and **bioturbation** limited in burial contexts)	[59]
Kiltyrie	NN 62550 37761	283820	Negative features (pits and postholes)	Unenclosed	**Agricultural attrition** (post-medieval ploughing); **reuse** (alteration and successive building in medieval and later medieval period)	[60]
King's Seat	NO 0093 4303	27172	Hillfort (multiple hearths and associated structures (probable); large rectangular structure; revetted platform; evidence of metalworking and craft production)	Enclosed	**Agricultural attrition** (post-medieval cultivation); **bioturbation** (extensive rhododendron growth and root disturbance; planted woodland; mammals); **slope** (site denuded through slumping and hillwash); **reuse** (**reuse** of rampart material for terraced track); **lack of stratigraphy/features** (result of extensive **bioturbation** in certain areas; possible use of exposed bedrock in early medieval period)	[61,62]

Table 1. *Cont.*

Site Name	NGR	Canmore ID	Settlement Evidence (Early Medieval)	Settlement Type	Post-Depositional Processes and Observations	References
Kinneddar	NJ 2243 6969	16459	Vallum ditches and enclosures; internal settlement features and structure (pits, postholes, clay floor layers)	Enclosed	**Agricultural attrition** (post-medieval and modern ploughing; field drain); **urban development** (truncation of features by modern graveyard and housing; modern waste pipe and sewer system); **reuse** (rebuilding in the medieval period); **moderate preservation** (fragmented but relatively good surface condition of bone assemblage–possible result of low soil acidity); **lack of internal stratigraphy/features** (no floor deposits or hearth in wooden building–structure not fully excavated)	[63]
Kintore	NJ 78739 16232	18584	Multiple structural features–two probable rectilinear buildings; multiple pits; features with *in situ* burning (possible kilns)	Unenclosed	**Agricultural attrition** (post-medieval and modern ploughing); **bioturbation** (soil biota); **reuse** (pit cut into Early Neolithic structure); **lack of internal stratigraphy/features** (reasons unclear–likely to be related to pedogenic processes; possible removal of hearth)	[64]
Lair	NO 1387 6376	29510	Multiple Pitcarmick-type buildings (seven buildings excavated)	Unenclosed	**Agricultural attrition** (medieval; modern vehicle tracks); **bioturbation** (mammals and roots–limited impact); **animal disturbance** (trampling and movement of artefacts); **reuse** (of Bronze Age ring-cairn stones); **lack of internal stratigraphy** (reason unclear–partly the result of post-medieval agriculture; floor layer only identified in one of seven excavated structures and had no clear stratigraphy)	[28,65–70]
Litigan [2]	NN 7666 4966	24945	Circular stone building (limited dating evidence)	Unenclosed	**Reuse** (extensive stone robbing and **reuse** of structure as dump); **poor preservation** (no bones identified–acidic soils); **lack of internal stratigraphy/artefacts** (compacted soil directly above undisturbed subsoil but no discernible floor–reasons unclear)	[71]
Macallan Distillery [3]	NJ 27825 44715	350336	Pits; roundhouse structures (possible)	Unenclosed	**Agricultural attrition** (modern ploughing); **bioturbation** (roots and invertebrates); **poor preservation** (highly fragmented and degraded burnt bone); **lack of internal stratigraphy/features** (ploughing)	[72]

Table 1. *Cont.*

Site Name	NGR	Canmore ID	Settlement Evidence (Early Medieval)	Settlement Type	Post-Depositional Processes and Observations	References
Maiden Castle	NJ 6942 2435	18182	Midden material; enclosures and ditches	Enclosed	**Agricultural attrition** (commercial forestry and 18th/19th C. drainage works); **reuse** (18th/19th C. activity and robbing)	[73,74]
Meadows Business Park	NH 797 895	123446	Ditched enclosures; sub-rectangular building; midden and multiple hearths associated with metalworking	Both	**Agricultural attrition** (medieval and post-medieval ploughing); **reuse** (remodelling/truncation of features in early medieval period)	[75]
Mither Tap (o' Bennachie)	NJ 6825 2240	85507	Hillfort (excavation of hearth; structure (possible) and associated surface)	Enclosed	**Reuse** (robbing and truncation of features by path)	[76,77]
Newbarns	NO 68474 49352	35394	Sub-rectangular building; pits	Unenclosed	**Agricultural attrition** (modern ploughing); **lack of internal stratigraphy/features** (reasons unclear–no hearth or occupation deposits; may have been on raised floor–structure not fully excavated)	[78]
Pitcarmick	NO 0598 5812	27250	Pitcarmick-type buildings (2) with hearths, paving and interior floor deposits	Unenclosed	**Agricultural attrition** (medieval and post-medieval ploughing; later construction of field walls); **bioturbation** (roots); **reuse** (alteration and reoccupation of structures in medieval period); **poor preservation** (highly fragmented burnt bone)	[27,79]
Portmahomack	NH 91485 84020	15662	Monastic settlement and burial ground (multiple structures and features)	Enclosed	**Agricultural attrition** (medieval and modern ploughing); **bioturbation** (mammals and invertebrates); **reuse** (redevelopment of structures and areas; possible robbing of earthworks and wall material); **good/differential preservation** (bone survival; wood preservation in waterlogged areas; areas of internal stratigraphy–clayey-silt/silt sequence; highest areas of site severely truncated by ploughing)	[80–91]
Rhynie	NJ 4974 2634	281408	Palisaded enclosure (multiple structures and features)	Enclosed	**Agricultural attrition** (ploughing and cattle scrape); **bioturbation** (mammals and roots); **reuse** (redevelopment during early medieval period); **differential preservation** (related to topographic variations and ploughing–increased truncation of deposits at top of knoll; bone mainly fragmented and burnt, but some unburnt remains in postpipes); **lack of internal stratigraphy** (reasons unclear–partly the result of plough erosion)	[92–98]

Table 1. *Cont.*

Site Name	NGR	Canmore ID	Settlement Evidence (Early Medieval)	Settlement Type	Post-Depositional Processes and Observations	References
Shanzie	NO 2791 5045	183018	Irregular cobbled surface; spread of carbonised cereal grain	Unenclosed	**Agricultural attrition** (modern ploughing); **bioturbation** (probable earthworms and others); **reuse** (of Iron Age souterrain; robbing in antiquity)	[99]
Upper Gothens	NO 1677 4152	28912	Palisaded enclosure (postholes and internal features)	Enclosed	**Agricultural attrition** (subsoiling, vehicles and drainage works); **bioturbation** (modern roots/weeds); **poor preservation** (of metal artefact; very low quantities of burnt bone and wood charcoal; recovery of single, badly preserved cereal grain)	[100]
Urquhart Castle	NH 53095 28647	12547	Structures with built hearths and cobbled surface	Enclosed (probable)	**Reuse** (destruction by fire–redevelopment in medieval period); **lack of internal artefacts/ecofacts** (no bone, pottery etc. in floor layer–reasons unclear)	[101]
Walton Road	NJ 872 113	332432	Metalworking features including trampled activity surface, structures (probable), hearths and pits	Unenclosed	**Agricultural attrition** (post-medieval and modern ploughing); **bioturbation** (mammals and roots); **reuse** (alteration of Iron Age structures and settlement)	[102–104]

Table Footer:

1. Hawkhill (Fife) is located 700 m NE of Easter Kinnear. Excavation of three scooped structures produced no dating evidence, however an early medieval date was inferred through typological similarity and proximity to the Easter Kinnear structure. The excavation and interpretation of both sites is reported in [57].
2. Queen's View–a similar structure located approximately 14km NE of Litigan–was also reported in the same literature [71]. Material culture gave a suggested date of AD 700-900 but was not supported by radiocarbon dating.
3. The early medieval dates for the structures at Macallan Distillery remain problematic and may be the result of contamination from an unidentified upslope early medieval settlement. The site has been included in this analysis owing to its structural similarity and geographical proximity with the Grantown Road examples. Further discussion is reported in [72].

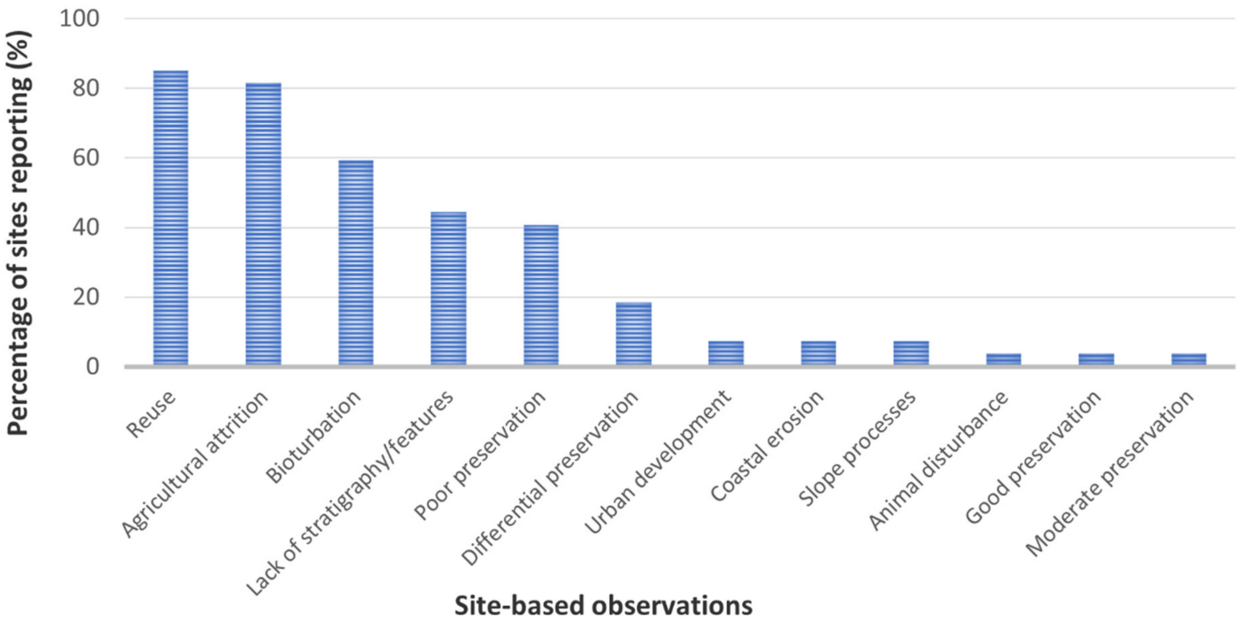

Figure 2. Percentage of sites in catalogue reporting evidence for each site-based observation ("Lack of internal artefacts/ecofacts" reported at Urquhart Castle (Table 1) has been grouped under "Lack of stratigraphy/features").

4.1.1. Reuse of Sites

The direct reuse or remodelling of settlement features was found to have occurred at 23 of the sites studied (85.2%). This included the reuse of earlier settlement features by early medieval populations (37.0% of total sites) as well as the modification and reuse of early medieval settlement (66.7% of total sites).

Many structures had been incorporated into already populated landscapes (e.g., Pitcarmick, Grantown Road, Carn Dubh, Walton Road, Lair) and there was a significant trend in which early medieval dwellings respected or utilised prehistoric remains. Remodelling within the early medieval period was also evident at a number of sites including Lair, Portmahomack, Easter Kinnear/Hawkhill (Fife) and Dunnicaer. At the latter, the construction of multiple successive hearths and structures was interpreted as a response to rapid expansion within a limited space (possibly exacerbated by the impact of coastal erosion [56] (p. 32)). Post-abandonment activity typically served to truncate or rework material, and significant robbing of building material was recorded at eight of the sites studied (29.6%).

4.1.2. Agricultural Attrition

Agricultural attrition was recorded in 22 of the 27 sites analysed (81.5%). The most significant cases related to truncation as a result of modern ploughing, where all surficial evidence had been destroyed and the sites existed as negative features cut into the subsoil (e.g., Grantown Road, Macallan Distillery, Walton Road, Newbarns, Rhynie). Many features had been completely removed and, where deposits did survive, they existed as little as 0.02 m deep (Newbarns) and were often contaminated with subsoil or cut by plough furrows [78] (p. 105).

Ancillary activities had caused damage at six of the sites catalogued (22.2%). At Upper Gothens, this had disturbed over 75% of the cleaned surface and obliterated all archaeological features in a 12–15 m length stretch of the site [100] (p. 35). At Rhynie, cattle trampling was found to have exacerbated the plough erosion following the field's conversion to pasture, resulting in a 9 m by 5 m erosion scar that exposed the subsoil [96] (p. 13).

Premodern agricultural activity was also recorded at 13 of the sites (48.1%), primarily in the form of ardmarks or rig and furrow. At Pitcarmick, this had removed walls, cut into floors, and spread material across the site. At Lair, plough furrows had accentuated the degradation of structures and contributed to the merging of turf wall and internal deposits [66] (p. 28). Notably, at Walton Road (where both modern and post-medieval ploughing had occurred), higher levels of truncation were observed in proximity to the remains of rig and furrow [103] (p. 33).

4.1.3. Bioturbation

The reworking of sediments by soil fauna was found to have had a significant impact at 16 of the sites studied (59.3%). In the most obvious cases, burrowing resulted in the truncation of features (Walton Road), unclear phasing (Rhynie), the movement of artefacts (Easter Kinnear, Lair) or the contamination of deposits with exogenous material (Newbarns, Macallan Distillery). Sites with sandy soils (e.g., Rhynie and Kintore) tended to report more significant impacts as a result of their loose and more easily penetrable soil structure. At Kintore, where the recovery of floor layers was limited, micromorphological analysis confirmed that the internal fabric of an early medieval structure had been destroyed through significant pedogenic processes including bioturbation, weathering and compaction [105] (p. 299).

4.1.4. Lack of Internal Stratigraphy/Features

Of the 22 sites that contained evidence of structures, 11 (50.0%) reported a lack of robust internal deposits. Those found in cropmark and greenfield sites typically presented with a complete lack of floor layers and very few internal features or finds (e.g., Rhynie, Grantown Road, Macallan Distillery).

An absence of floor deposits was also recorded at cropmark sites where structures had an erosional hollow or "scooped" component. No interior features were identified in the sunken building at Easter Kinnear, despite it surviving 1.5 m below the modern ground surface [57] (p. 83). Discovery of rough stone paving in a similar structure at nearby Hawkhill (Fife) suggested that a floor may have been removed prior to infilling; however, this too was unaccompanied by evidence of occupation deposits or a hearth. The later wattle-and-daub constructions at Easter Kinnear demonstrated a similar lack of floor layers, the reasons for which are unclear [57] (p. 89).

In upland sites where modern ploughing had not been a primary factor and structures remained upstanding (e.g., Carn Dubh, Lair, Litigan), interior deposits were similarly absent or had no coherent stratigraphy. Of the seven sub-rectangular buildings excavated at Lair, only Building 3 produced partial evidence of a possible floor layer. This was identified through its association with material culture (pottery, spindle whorl, burnt bone etc.) but was thin, and could not be mapped across the extent of the structure [28] (p. 112).

A notable exception to this trend was Portmahomack, where a clayey-silt/silt sequence was interpreted tentatively as the accumulation, or deliberate maintenance, of a beaten earth and ash floor [87] (p. 13). Occupation deposits were similarly evident at Dunnicaer and Burghead; however, truncation meant that the nature of the structures, or the degree to which their deposits represented the full extent of a building, were difficult to establish. At the former, this had resulted from the partial collapse of the sea stack, whilst, at the latter, it was due to the absence of evidence for enclosing walls [48]. Floor deposits were also recorded at Pitcarmick, though the site reports offered no indication over their condition or nature [27] (pp. 160, 171).

4.1.5. Preservation (Survival of Ecofacts/Artefacts)

Commentary on the preservation of artefacts and ecofacts primarily highlighted the relatively poor survival of organic remains. Plant remains were typically only recovered in carbonised form, and interpretations regarding past agriculture or land use were often limited by low count numbers and poor preservation (e.g., Carn Dubh [50] (pp. 176–178); Hawkhill (Angus) [59] (p. 41–45)). At Ardownie, 60–80% of the pollen recovered was classed as corroded or degraded, indicating substantial alteration of the original pollen record through processes such as oxidation and microbial activity [42] (p. 38–39).

Where recovered, bones were also found to be poorly preserved and typically only survived as small fragments of calcified material. This was largely attributed to aggressive conditions in free-draining acid soils; at Pitcarmick, ploughing and reuse for fuel were also put forward as potential post-depositional agents [27] (p. 181). More substantial bones were recovered at Rhynie (unburnt cattle remains in postpipes and a possible stone socket) and in the early medieval burial context at Hawkhill (Angus) but again their preservation was relatively poor, and this degree of survival was not consistent across either site.

Partial waterlogging at Portmahomack had resulted in the preservation of wooden artefacts, and the areas in and around Structure 9 were found to be exceptionally rich in well preserved cattle bones. Though lacking in organic materials, the artefact assemblage from Rhynie was equally impressive, producing more than 1000 artefacts over five seasons of excavation [98] (p. 76). This included significant evidence of metalworking, such as clay moulds, crucible fragments, crucible stands and metal tongs [9,97]. However, aside from these high-profile sites—where the majority of evidence related to on-site manufacturing—excavations typically produced few artefacts.

4.2. Phase 2: Comparison with National Data

Values and soil information collected for each site are recorded in Table 2. The degree to which these national data corresponded to the site-based literature is expressed geographically in Figure 3 and calculated as a percentage in Figure 4. Evidence relating to coastal erosion has been considered separately in Table 3 and Figure 5.

The assessment of similarity found a relatively high degree of correspondence across three of the national datasets (Chart A in Figure 4). The LCM2015 (land cover) proved to be the most accurate, with 85.2% of the comparable data having a Similar or Very Similar match with the site-based evidence. The SIFSS (soil description) produced a similar result, with 79.2% of the comparable data falling into these positive categories. The Soils of Scotland Topsoil pH dataset (acidity) had a slightly lower comparability, with 62.5% of the data having positive correspondence. When considering the total degree of similarity from all 27 sites (Chart B in Figure 4), this latter dataset had a much lower total comparability, with only 37.0% of the data falling into the Similar or Very Similar categories. This was largely the result of site reports not containing an assessment of the soil acidity or any evidence for the degradation/preservation of archaeological material.

In contrast to these datasets, the coastal erosion models were found to reflect site-based observations poorly. Whilst the NCCA Dynamic Coast did identify historic erosion on the north-west side of Burghead, it failed to return any information for Dunnicaer. The shoreline of a small bay to the north of the site was shown to have increased by over 16.5 m since 1967, but this is clearly an unsuitable proxy for the extensive erosion observed at Dunnicaer sea stack.

The CESM was similarly problematic, having categorised the north-west side of Burghead (an area considered to be most at risk of future loss [49]) as having a Low Susceptibility for coastal erosion. Whilst Dunnicaer's location as a sea stack meant that it was not directly included in the mapping, its associated coastline was categorised as Very Low susceptibility—a clear contradiction to the site-based observations.

Table 2. National dataset values and information assigned at early medieval settlement site NGRs.

			Soil Information and Properties			
Site Name	**Land Cover Category**	**Topsoil pH (Median)**	**Association and QMUNIT**	**Series and Coverage in Unit (%)**	**Soil Type**	**Drainage**
Ardownie	Arable and horticulture	6.40	Mountboy (414)	Mountboy (70%)	Brown earth with gleying	Imperfect
				Garvock (30%)	Brown earth	Free
Battle Hill	Coniferous woodland	5.61	Insch (316)	Insch (100%)	Brown earth	Free
Burghead	Suburban	5.70	Links (380)	Links (reg) (100%)	Noncalcareous regosol	Free
Carn Dubh	Coniferous woodland	3.80	Strichen (499)	Gaerlie (100%)	Peaty gleyed podzol	Free below iron pan
Craig Phadrig	Coniferous woodland	3.85	North Mormond (425)	Phorp (50%)	Humus-iron podzol	Free
				Urchany (50%)	Humus-iron podzol	Imperfect
Dunnicaer	-	-	Stonehaven (490)	Stonehaven (70%)	Brown earth with gleying	Imperfect
				Shields (30%)	Humus-iron podzol	Free
Easter Kinnear / Hawkhill (Fife)	Arable and horticulture	5.61	Gleneagles (273)	Gleneagles (100%)	Brown earth	Free
Grantown Road	Improved grassland [1]	5.90	Corby (97)	Boyndie (50%)	Humus-iron podzol	Free
				Corby (50%)	Humus-iron podzol	Free
Hawkhill (Angus)	Arable and horticulture	5.90	Alluvial (1)	Loamy wet (25%)	Mineral alluvial	Poor
				Sandy wet (20%)	Mineral alluvial	Poor
				Sandy dry (20%)	Mineral alluvial	Free
Hawkhill (Angus)	Arable and horticulture	5.90	Alluvial (1)	Peaty (pal) (15%)	Peaty alluvial	Poor
				Loamy dry (10%)	Mineral alluvial	Free
				Silty clay (10%)	Mineral alluvial	Poor

Table 2. *Cont.*

			Soil Information and Properties			
Site Name	**Land Cover Category**	**Topsoil pH (Median)**	**Association and QMUNIT**	**Series and Coverage in Unit (%)**	**Soil Type**	**Drainage**
Kiltyrie	Acid grassland	3.96	Strichen (503)	Strichen (85%)	Humus-iron podzol	Free
				Hythie (15%)	Peaty gley	Poor
King's Seat	Broadleaf woodland	4.65	Strichen (508)	Strichen (brank) (35%)	Brown ranker	Free
				Fungarth (35%)	Brown earth	Free
				Strichen (30%)	Humus-iron podzol	Free
Kinneddar	Arable and horticulture	5.90	Corby (97)	Boyndie (50%)	Humus-iron podzol	Free
				Corby (50%)	Humus-iron podzol	Free
Kintore	Suburban	5.69	Countesswells (115)	Countesswells (100%)	Humus-iron podzol	Free
Lair	Heather	3.96	Strichen (503)	Strichen (85%)	Humus-iron podzol	Free
				Hythie (15%)	Peaty gley	Poor
Litigan	Improved grassland	6.02	Strichen (505)	Fungarth (100%)	Brown earth	Free
Macallan Distillery	Arable and horticulture	6.20	Craigellachie (140)	Craigellachie (100%)	Humus-iron podzol	Imperfect
Maiden Castle	Coniferous woodland	4.03	Countesswells (117)	Charr (100%)	Peaty gleyed podzol	Free below iron pan
Meadows Business Park	Suburban	5.90	Corby (97)	Boyndie (50%)	Humus-iron podzol	Free
				Corby (50%)	Humus-iron podzol	Free
Mither Tap(o' Bennachie)	Heather	4.03	Countesswells (117)	Charr (100%)	Peaty podzol	Free below iron pan
Newbarns	Arable and horticulture	5.90	Corby (97)	Boyndie (50%)	Humus-iron podzol	Free
				Corby (50%)	Humus-iron podzol	Free
Pitcarmick	Heather	3.80	Strichen (504)	Gaerlie (35%)	Peaty gleyed podzol	Free below iron pan
				Hythie (35%)	Peaty gley	Poor
				Semi-confined peat (30%)	Dystrophic semi-confined peat	Poor

Table 2. *Cont.*

			Soil Information and Properties			
Site Name	**Land Cover Category**	**Topsoil pH (Median)**	**Association and QMUNIT**	**Series and Coverage in Unit (%)**	**Soil Type**	**Drainage**
Portmahomack	Improved grassland	6.28	Nigg (420)	Nigg (reg) (50%)	Regosol	Free
				Pithogarty (50%)	Humus-iron podzol	Free
Rhynie	Improved grassland	5.90	Corby (97)	Boyndie (50%)	Humus-iron podzol	Free
				Corby (50%)	Humus-iron podzol	Free
Shanzie	Arable and horticulture	5.61	Gleneagles (273)	Gleneagles (100%)	Brown earth	Free
Upper Gothens	Arable and horticulture	6.00	Forfar (239)	Forfar (50%)	Humus-iron podzol	Imperfect
				Vinny (50%)	Humus-iron podzol	Free
Urquhart Castle	Improved grassland	4.37	Sabhail (457)	Findon (50%)	Humus-iron podzol	Imperfect
				Sabhail (50%)	Peaty gleyed podzol	Imperfect
Walton Road	Arable and horticulture	5.69	Countesswells (115)	Countesswells (100%)	Humus-iron podzol	Free

Table Footer:
1. "Improved grassland" is characterised by vegetation dominated by a few fast-growing grasses such as *Lolium* spp that are typically managed as pasture or mown for silage production or, in non-agricultural contexts, for recreation and amenity purposes. Further descriptions of the land cover categories can be found in the dataset documentation [106].

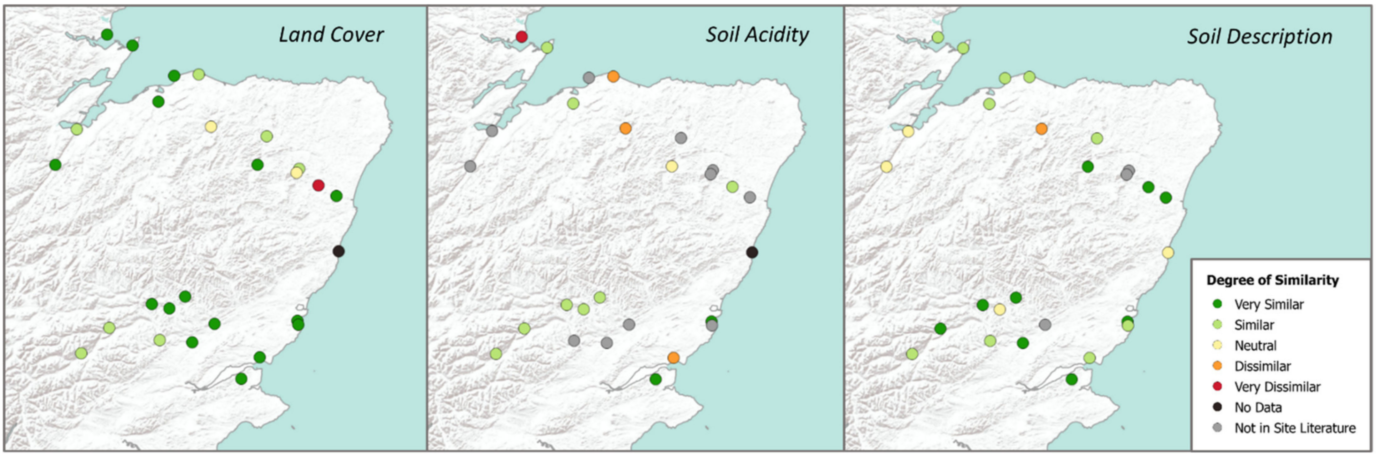

Figure 3. Geographic distribution of Phase 2 similarity analysis.

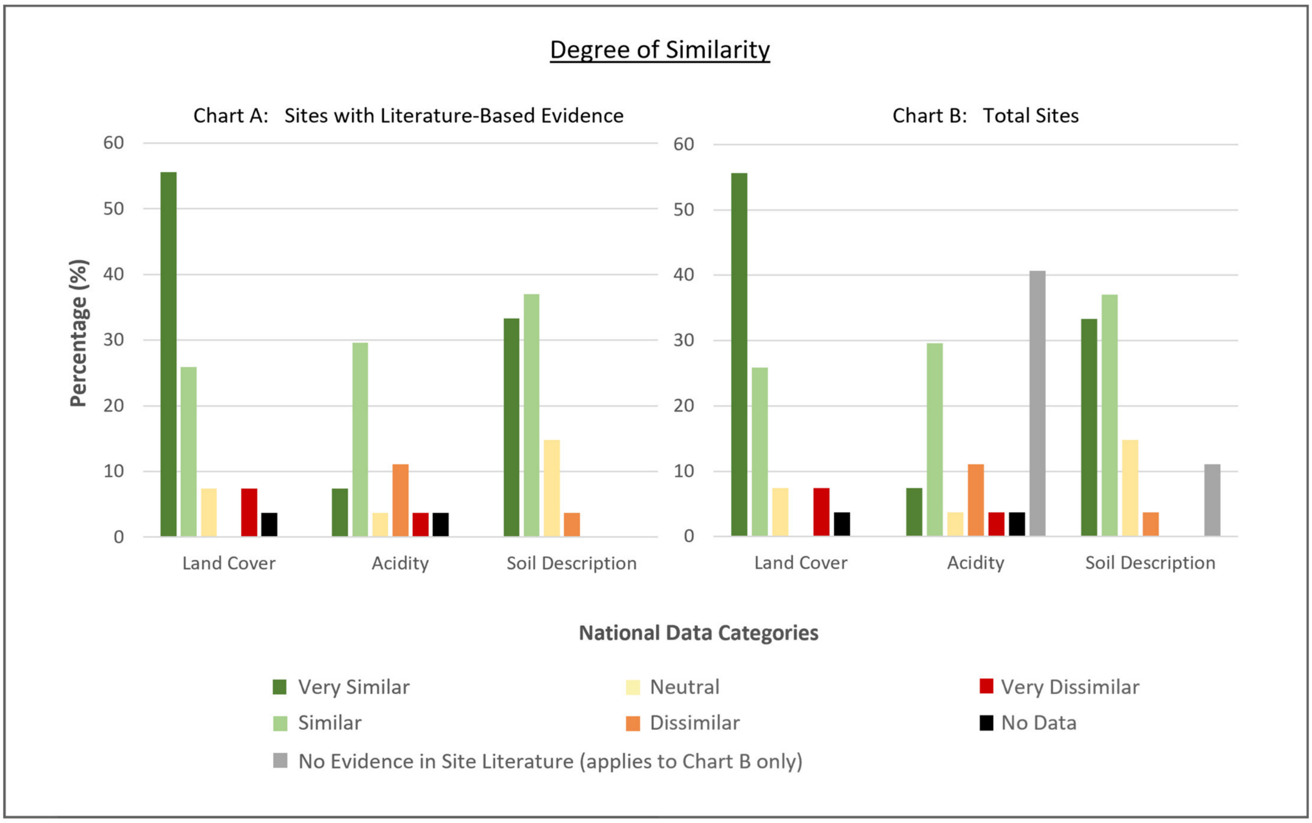

Figure 4. Overall percentage of each comparison category (Chart A = % of study sites with literature-based evidence for comparison (n = total number of sites (27)—number of sites with no evidence in the literature); Chart B = % of total number of study sites (n = 27)).

Table 3. National dataset and model evidence for coastal erosion at study sites.

Site Name	Coastline Type	Site Area Mapped		Evidence	
		NCCA	*CESM*	*NCCA*	*CESM*
Burghead	Hard and mixed/artificial	Yes	Yes	• Between 7 m and 8 m of erosion occurring on the NW side of the site between 1904 and 2011 [1] • Between 2 m and 2.5 m of erosion occurring on the NW side of the site between 1976 and 2011 • Future erosion at site not projected (significant future erosion indicated in proximity to Burghead; up to 22 m of erosion since 1976)	• Categorised as Low Susceptibility on NW face of site • Medium Susceptibility on N face of site • High Susceptibility in area of artificial harbour (on W side)
Dunnicaer	Har and mixed	No	Yes	- (future accretion indicated in proximity to the stack; up to 16.5 m of accretion since 1967)	• Extent of site not directly mapped • Coastline categorised as Very Low Susceptibility

Table Footer

1. Coastline data grouped under 1890, 1970 and modern MHWS (Mean High Water Spring–see Figure 5, frame (b)), but more accurate survey dates can be identified by clicking the mapped survey lines on the Dynamic Coast webpage [34].

Figure 5. Coastal erosion models for early medieval study sites ((**a**)—Dynamic Coast shorelines for Dunnicaer and proximity; (**b**)—Dynamic Coast shorelines for Burghead and proximity (inset showing shorelines on NW face); (**c**)—CESM data for Dunnicaer and proximity (inset showing aerial view of site and extent of erosion); (**d**)—CESM data for Burghead).

5. Discussion

5.1. Post-Depositional Processes

Given that the majority of sites were situated on arable or improved land (Table 2), it is unsurprising that agricultural attrition was one of the most significant processes affecting early medieval remains, both in the extent of destruction and the number of sites affected. This finding is consistent with broader studies that identified agriculture to be the most significant and widespread threat to both the UK and the world's archaeological resource [107–115].

The most severe damage typically occurred through episodes of modern ploughing, and thus predominately affected sites in the arable zones of the lowlands (e.g., Rhynie, Upper Gothens, Newbarns). Experimental work has shown that, in these contexts, repeated ploughing can truncate sites by 0.07–0.1 m over a 30-year period [111] (p. 17–18). Several deposits within the arable sites lay within this threshold, indicating they may be lost within just a few decades of their excavation. The most obvious candidate for this loss is Newbarns, where the average surviving depth of excavated features was around 0.2 m, and some deposits were as shallow as 0.02 m [78]. In 2004, disturbed subsoil was recorded on both scheduled and unscheduled areas around the site, and discussions with the landowner indicated that penetrating the subsoil was unintentional and had most likely resulted from the plough cutting into slight elevations in the subsoil [116] (p. 31). Similar impacts were identified at Rhynie and Portmahomack, which both reported increased erosion on areas of topographic variation, such as knolls and crests [86] (p. 4), [98] (p. 69). Over time, these cases of imperfect ploughing contribute to the effective deepening of cultivation and the planing of archaeological deposits, but are likely to go unrecorded unless excavation or monitoring efforts are repeated [117].

One approach is to afford sites increased legal protection as Scheduled Monuments, effectively limiting the extent to which penetrative cultivation can occur. However, the legislation cannot control agricultural practices if it is shown that such activities occurred on the land within the previous ten years (Ancient Monuments (Class Consents) (Scotland) Order 1996). This means that ploughing can occur at a consistent depth even when ploughsoil thinning is observed, effectively bringing archaeological deposits closer to the zone of erasure. This was evidenced at Rhynie, Newbarns and Kinneddar, all of which had been afforded Scheduled status prior to excavation. A study of scheduled monuments in England (which are protected by similar legislation—Ancient Monuments (Class Consents) 1994) also found a considerable percentage of farmers had broken this Class Consent agreement, with 25% of the sites surveyed being subjected to deep ploughing and subsoiling [110] (p. ix). Given the evidence for truncation and subsoil disturbance, it is clear that early medieval settlement sites within the arable zone are at an increased risk of destruction and require a more effective management strategy.

Obliteration as a result of modern ploughing is one of the theories put forward for the general lack of early medieval settlement observed across Scotland [20]. Certainly, the use of more ephemeral building materials (turf or timber wattle) would result in less robust archaeological signatures; however, the high degree of reuse observed in the case study—both of previous settlement features and of early medieval structures—suggests that new sites may be eluding researchers simply as a result of their location amongst more prominent remains. The structures at Pitcarmick are located in a densely populated landscape, with remains stretching from the prehistoric to the 18th century, and they were not recognised as being of an early medieval date until a programme of survey and excavation in the late 1980s–1990s [27,118]. At Grantown Road and Macallan Distillery, the 9th to 12th century roundhouse structures had to be identified through radiocarbon dating, as the form was deemed unusual for such a late date and had no obvious parallels [58] (p. 69), [72] (pp. 19–20). There is also clear evidence for the reuse of hillforts and defensive structures and, in areas where early medieval settlement continues to elude researchers (e.g., Argyll), further examination of both populated landscapes and defended sites is likely to offer much needed detail.

Yet, even with the addition of new sites, a number of post-depositional processes are limiting the extent to which we can understand the settlement record. The decomposition of organic material in Scotland's free-draining, acidic soils means that much of our understanding of manufacturing, status and society has come from metal artefacts [96,98]. These are largely restricted to high-status settlements and we are missing a wealth of detail from more rural settings. Whilst understanding soil conditions and drainage environments may help to identify areas where such artefacts can survive, many soils are expected to undergo increased desiccation as a result of climate change, and the opportunity to find such examples is limited [22] (p. 34). Environmental inputs are an additional concern, with studies demonstrating that the deterioration rate of artefacts—particularly inorganic materials—has accelerated in recent decades as a result of anthropogenic pollution [119,120]. To date, this has been linked to the limited number of metal finds observed on the Swedish west coast, whose acidic soils provide a point of comparison with the Scottish mainland [120] (p. 261). It has already been shown that Scottish soils have undergone considerable acidification in recent years [121] (p. 15), and failure to acknowledge this threat will result in a further loss of the settlement record.

This poor artefact preservation, coupled with a lack of occupation deposits or stratigraphy, has created an uncomfortable trend in which questions over economic activity and the organisation of social space often go unanswered. This problem is not unique to the north-east and has caused particular issue in the study of Norse Atlantic Scotland. Stratigraphy at the western settlement of Brough of Birsay in Orkney was found to be surprisingly shallow [122,123] (p. 16) and, despite being described as "the best preserved long-house in Scotland", the multiple phases of activity and rebuilding at Hamar longhouse in Shetland had only partially survived later activity and erosion [124]. The top layers of soil had been stripped at some point in the site's history and very few artefacts were recovered during its excavation.

The removal of internal deposits—intentionally or otherwise—provides one explanation for the general lack of stratigraphy observed across early medieval structures. In this scenario, cultivation or reuse are likely to be the primary agents; however, other anthropogenic factors include the use of floor coverings or maintenance practices that would have removed occupation build-up [31] (pp. 226–234), [125,126] (pp. 115–156), [127] (pp. 598–599). The preserved floor layers at Portmahomack certainly suggest episodes of regular maintenance, and remains from Underhoull Viking longhouse in Shetland have pointed towards the use of a wooden sprung platform that would have supported a hearth and kept the floor dry [123] (p. 16), [124]. This could explain the lack of hearths at Newbarns or Easter Kinnear; however, without comparative examples or more detailed evidence, the application of these practices within Scotland's early medieval period remains unresolved.

The mixing of sediments by roots and soil fauna offers another explanation. Within the study area, sites appeared particularly susceptible to mammalian burrowing activity as they often comprised "soft" deposits such as turf and earthworks, or were located on sandy subsoils whose loose soil structure could be easily penetrated. Micromorphological analysis conducted at Brotchie's Steading in Caithness (a multi-period settlement mound) has shown that invertebrates can have an extreme impact on archaeological deposits, with high levels of earthworm activity being responsible for the reworking of early medieval turf deposits into homogenous soils [128,129] (p. 274). Earthworms are the primary bioturbators in temperate soils, however their impact on archaeological sites is largely recognised through thin section analysis and may be missed if such techniques are not routinely employed [130,131]. This type of analysis has not yet been conducted on early medieval upland sites, and there is little evidence to support or deny the role of invertebrates in their alteration (although these sites were found to have the lowest pH values (Table 2) and studies have indicated that earthworm activity is likely to be limited at sites with very low pH [132]). The evidence from settlement in arable and grassland sites is more conclusive, with bulk analysis and micromorphology successfully identifying the remains of invertebrates, as well as their eggs and excreta [72] (p. 15), [105] (p. 299).

Buried remains in Scotland are expected to undergo increased rates of bioturbation as a result of climate change, where longer growing seasons will encourage the spread of new and invasive species, and deeper and more extensive root growth [22] (p. 33). A potential acceleration in the loss of soil stratigraphy should therefore prompt a review of the way these sites are investigated, and efforts should be made to understand not only the early medieval activity but also the rate and scale of degradation at site level.

5.2. Use of National Datasets

The relatively high degree of correspondence between national datasets and site-based observations suggests that these freely available resources could be used in an archaeological context (Figures 3 and 4). As the datasets relate to modern values, their application will be best suited to remote assessments of current or projected risk; this could include scheduling applications, monument monitoring, conservation efforts or identifying candidates for rescue excavation. To this end, the LCM2015 is arguably the most valuable dataset for UK-based analysis, as the synonymity between land cover and land use permits an evaluation of the different levels of threat or protection afforded to archaeological remains (e.g., sites within an active arable zone are more at risk of attrition than those with heather covering, whilst areas of uncultivated land may be more at risk from rabbit burrowing [116] (p. 71), [133] (p. 1)).

However, categories within the dataset are relatively broad and direct application of the data could fail to address a wide variation in the extent and nature of post-depositional processes. The Arable and Horticulture category, for example, covers all active cultivation regimes and is unable to account for the different levels of threat associated with crop types (e.g., the deep ploughing regime required for potatoes is likely to be more harmful to subjacent archaeology than cereal crops [116] (p. 71)). Associated maps which directly characterise the arable land into specific crop parcels are available under an institutional licence and are likely to provide greater detail for these sites (UKCEH Land Cover® plus: Crops 2015, 2016, 2017, 2018 and 2019).

The LCM2015 also highlighted a broader issue over a lack of information regarding the impact of different land and vegetation covers on archaeological monuments. The best-preserved sites in the case study (Pitcarmick and Lair) had heather land cover, which is often subjected to controlled burning as a means of erosion control and vegetation management. There is currently no available literature addressing the impact of heather or its burning on archaeological monuments and it is clear that, if land cover data is to be of any real value, more detailed studies are needed to characterise these impacts [134] (p. 11).

Combining information is likely to more effectively utilise the datasets, as land cover and soil descriptions can be used to infer the likelihood that particular processes have impacted archaeological landscapes. For example, in an agricultural context, the loosely structured, free-draining sandy soils of the Boyndie Association are unlikely to require de-stoning, extensive drainage programmes or subsoiling to remove compaction pans [116] (p. 30). In sites susceptible to periodic waterlogging, the reverse may be true. At Upper Gothens, where archaeological remains had been extensively damaged due to subsoiling, drainage works and heavy machinery bogging down in wet conditions [100], the LCM2015 was able to identify that the site was in active agricultural land, whilst the SIFSS indicated it was situated on a soil with imperfect drainage (Table 2).

In contributing to the soil information, the Soils of Scotland Topsoil pH map does appear to provide a suitable proxy for site acidity; however, the evaluation was limited by a lack of numerical data in the literature. Few reports directly commented on the acidity of a site, and even fewer had actually conducted pH assessments. Therefore, the degree to which the data corresponded had to be based on descriptions of degradation rather than comparable values. This introduced a range of interpretational biases and it is currently not possible to say whether national pH mapping is a suitable way to estimate this aspect of the preservation environment.

A methodological issue recognised over the course of this study related to the fact that values and information for each site were established using a single grid reference. This only reflects one point in an archaeological landscape and introduces a geographical bias with regards to where data are collected. This was particularly pronounced in larger sites such as Portmahomack, where excavations occurred on both pastural and arable lands, as well as within an upstanding church. Future applications could overcome this by examining the wider area of the site or, for the pH dataset, taking point values across the area to check for erroneous results.

The poor correspondence between site-based observations and national coastal erosion models suggests that these are currently unsuitable for the remote assessment of coastal sites. Though just two sites were analysed, these findings are consistent with the case study on Sanday, Orkney, that found neither model to be a suitable reflection of erosional events [35].

Given the lack of evidence for early medieval settlement recovered from present-day urban contexts, a comparison of national datasets with urban sites could not be achieved. However, neither the topsoil pH dataset nor the soil description dataset (SIFSS) provide values for densely populated urban areas such as cities, instead characterising them with a pH value of 0 or QMUNIT 608 (Association: Built-Up) respectively. As such, national datasets are currently unable to provide a method of preservation assessment in modern urban contexts.

It is also recognised that the preservation factors assessed in this study (land use, soil acidity, soil type) do not exclusively determine the retention or decay of archaeological materials. Factors such as soil compaction, soil water level and organic matter content are significant contributors that can also influence a number of other preservation conditions. For example, dewatering can result in the shrinkage or erosion of deposits, increased biological activity, increased acidity and the corrosion of artefacts [135] (p. 3). However, such conditions are rarely considered, much less characterised, during excavation or site-monitoring, and the relationship between these factors and our understanding of how archaeology responds to changing soil properties remains limited. In Scotland, national soil surveys on water capacity [136], organic carbon concentration [137] and erosion and compaction risk [138–140] have the potential to inform and predict these processes, however their use is currently restricted by a lack of comparative detail at the site-level.

Finally, a lack of national data relating to important post-depositional processes, such as bioturbation and fluctuating groundwater, means that remote assessment can only offer information on certain aspects of the preservation environment. There are currently no national archives regarding soil macrofauna, earthworm populations or redox conditions, and thus we are missing a significant understanding of the relationship between different land covers, soil types, pH and animal activity. Moreover, bioturbation was only partially explored in the excavation literature and, in order to understand the prevalence of this process across early medieval sites or Scotland's archaeological resource more broadly, further soil surveys and dedicated case studies are required.

5.3. Implications for Future Practice

As highlighted above, preservation potentials across Scotland's early medieval settlement sites are relatively poor and are set to change further over the coming decades. The assumption that archaeological material is best preserved in situ is quickly losing credence among both researchers and heritage bodies, and alternative strategies are being considered at all levels of care [21,22]. In situations where negative conditions cannot be halted, reversed or significantly impeded, excavation is now being actively promoted as a management plan [22].

To ensure that these strategies are administered appropriately, heritage managers must be able to estimate the current and projected risk faced by specific archaeological sites. The methods outlined in this study have offered one means of considering preservation and risk, but equally highlight the issues associated with basing an analysis solely on a literature review or generalised and proxy data. A handful of countries have developed risk maps as a more rational and economical means of undertaking the management of archaeological monuments, but these almost exclusively deal with upstanding or architectural remains, and the analysis of risk typically concentrates on catastrophic events such as earthquakes and flooding [4–6], or the long-term effects of pollution, tourism, erosion and climate change [5,7,8]. By contrast, risk maps concerning buried heritage, or the post-depositional events experienced at the soil interface, are noticeably lacking. As this study has demonstrated, national soil datasets can provide some broad indications of risk that are of value to heritage managers, but major factors are missing, and the mapping resolution is ultimately too low for site-specific management [141] (pp. 54–60).

However, there is still considerable potential for these resources to inform archaeological risk mapping if combined with site-based evidence collected from excavations and monitoring efforts. Such a resource would need to be dynamic and regularly updated as more information is made available about conditions at the site-level. This would produce a dataset that not only indicates risk but actively encourages research into post-depositional processes, the relationships between factors, and how the different aspects of settlement (architectural styles, building materials, longevity of use etc.) can influence these impacts. However, as this study has shown, observations made at the site-level need to be more detailed and include empirical data that can be directly compared against sites and across geographical and environmental settings.

Excavation is the most direct means of accessing information related to preservation conditions but the methods used can also cause interpretational issues. Keyhole excavation has been the most widely applied strategy in the assessment of Scotland's early medieval settlement but has often failed to highlight areas of good preservation or provide any meaningful commentary on the overall condition of a site [23]. "Strip-and-map" recording methods—in which large trenches are opened, cleaned and mapped—were used at both Rhynie and Portmahomack, and proved valuable in providing a more complete evaluation of the sites [84,142]. However, this technique has seen limited uptake in commercial contexts, as it requires a large workforce and can often fail to address some of the more detailed questions regarding preservation and natural or cultural formation processes [142] (p. 556). Removing such a large quantity of topsoil can also leave sites vulnerable to intrusion or make them more susceptible to the damaging impact of cultivation. Whilst compaction of the soil following reinstation is believed to mediate these issues, there is not yet a body of evidence to assure minimal impact [142] (p. 556).

Moving forward, the most valuable approaches will be those that clarify both the post-depositional processes and their agents, as well as those which provide the empirical data required for comparative analysis. Geoarchaeology is an obvious candidate, offering a range of techniques that can be applied at a variety of scales and to different environmental and cultural contexts. At Bornais, on the island of South Uist, for example, micromorphology was able to identify that 7th–9th century AD occupation deposits had been altered through episodes of trampling, digging and maintenance, as well as the addition of turf and hearth material [143]. At the multi-period settlement site of Old Scatness in Shetland, this technique was combined with phosphate analysis and particle-size distribution in order to track changes to agricultural methods over time. The analysis of arable soils revealed that domestic waste, floor material and ash were all used as soil amendments for much of the Iron Age, but that organic material only became an integral part of the manuring strategy towards the middle of the first millennium AD [144,145]. This increase in animal manure indicated a change in the relationship between arable farming and livestock husbandry, and offered insight into the increasing organisation of the resources required for agriculture [145] (p. 84).

However, across Scotland, much of the work to date has been concentrated in the Northern or Western Isles, and comparative work on mainland sites is somewhat lacking. This is particularly true across sites dated to the first millennium AD, which, given their tendency for poor preservation, is in need of addressing. Chemical analysis (phosphate and multi-element by XRF) has been employed in an attempt to locate hearths or identify activity "hotspots" on mainland early medieval sites, but interpretations of the results rarely go beyond presence/absence (e.g., [65] (p. 9), [146]). Micromorphology has proven to be a more effective tool, having recognised maintenance practices, post-depositional mixing by invertebrates, and the eluviation of fine material by rainwater (e.g., [105] (p. 299–300)). However, again, there are gaps in the knowledge, with significant sites such as Pitcarmick having not benefitted from the application of the technique or the publication of its results. Studies outside Scotland have already highlighted the ability of this technique to identify occupation deposits and activity areas that are not apparent during excavation (see [147]) and, given the lack of stratigraphy observed across the study area, this should be a significant consideration for future research.

Given that many of the questions regarding preservation conditions occur across a range of environmental settings, comparing micromorphological samples from different contexts may be an appropriate place to start. Alternative applications of geoarchaeological techniques include the monitoring of soil conditions at sites where in situ preservation is practised [135,148]. Historic Environment Scotland have noted that their current monitoring practice is not sufficient for scheduled monuments buried beneath the ploughsoil and does not produce data that can be combined or compared against other monument types [117]. Geochemical analysis has also been shown to improve the results of geophysics in Scottish contexts [149], and further developing this relationship may yet result in the identification of sites in contexts where current archaeological approaches have failed. As of yet, there are no guidelines for the application of geoarchaeology in Scotland, and future excavations would likely benefit from such documentation.

6. Conclusions

The analysis conducted in this case study has highlighted a number of factors with significant implications for both early medieval Scotland and settlement research more broadly. First, and perhaps most obviously, it has identified that the condition of each site is the consequence of multiple natural and anthropogenic events. Primarily, these relate to the destruction, removal or alteration of the archaeological record, and by presenting a spectrum of observed data, it has been possible to identify the factors most likely to affect early medieval sites across a range of environmental contexts. Agriculture and reuse have already dealt significant damage to the settlement record but equally offer a place to look for new sites and begin addressing questions concerning geographic lacunae. In considering the future of Scotland's early medieval settlement remains, the identification of widespread bioturbation, aggressive soil environments, coastal erosion and continued agricultural attrition is paramount. The threat posed by each of these processes cannot be understated and, as climate change continues to alter and accelerate their nature, the way we approach the archaeological record becomes vitally important.

Moving forward, the ability to predict sites most at risk of alteration (or those that currently have the best examples of preservation) will be critical in ensuring effective management. National soil datasets have the potential to form the basis of heritage risk maps that focus on post-depositional processes but are of limited value in their current form. Should they be incorporated into a dynamic map, they would provide a useful foundation to which higher resolution data could be added. New excavations and monitoring efforts which directly incorporate questions about the preservation environment into their research design will therefore be key in addressing the current absence of detail.

Although this evaluation used eastern Scotland as a case study, the implications extend beyond its regional bounds. The comparison of site-based evidence with national datasets offers a means to develop a foundational understanding of the factors impacting archaeological preservation, and to recognise key knowledge gaps in both the archaeological corpus and wider resources. This can be adapted to cover any temporal scale and would be particularly effective in circumstances where post-depositional events are unclear or have proven difficult to access. In such cases, the results are likely to produce more comprehensive interpretations and shape more effective management strategies. Moreover, international studies are likely to identify trends in post-depositional processes and create a broader understanding of how the various aspects of settlement (e.g., architecture, building material and longevity of use) influence states of preservation and post-depositional signatures. It is therefore hoped that, by providing a methodology that can be applied worldwide, the current study will prompt a review of how we approach site formation histories and the tools that can be used to consider both past and future threats.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/heritage4020041/s1, Document S1: List of search terms used in analysis of excavation literature.

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Data Availability Statement: The data presented in this study are available within the body of the article. Reports contributing to the data are largely published; however, occasional restrictions do apply to their availability. Where reports were unpublished, data were obtained by the corresponding author and have been used with permission. The national datasets are freely available and can be accessed via their online hosting platforms (links supplied in the References section of this article).

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Appendix A

Ranking criteria used to assess degree of similarity in Phase 2 of the Methodology (Article Section 3.2). For all tables: VS = Very Similar; S = Similar; N = Neutral; D = Dissimilar; VD = Very Dissimilar; ND = No Data; NR = Not Reported.

Table A1. Land cover.

VS	Identical/near identical description (e.g., pine forest vs. coniferous woodland)
S	Similar description (e.g., woodland vs. coniferous woodland)
N	Land cover difficult to establish in site report; not explicitly stated and may be inferred from other details; neither agrees nor disagrees with national data
D	Descriptions do not match well and would fall into different categories, but there is a degree of association (e.g., improved grassland vs. arable)
VD	Descriptions would fall into different land cover categories with no common element (e.g., urban vs. arable)
ND	No national data
NR	Land cover type not mentioned in site report

Table A2. Soil acidity.

VS	Very close match with site report (e.g., pH value of ~4 vs. "very acidic" or very similar value)
S	Similar match with site report (e.g., pH value of ~4 vs. "acidic" or similar value); acidity/alkalinity may not be explicitly clear in site report and may have been inferred from degradation levels
N	Conflicting evidence of acidity/preservation environment in site report; not clear whether national data agrees or disagrees
D	Dissimilar match with site report (e.g., pH value of ~4 vs. "moderately acidic" or significantly different value); acidity/alkalinity may not be explicitly clear in site report and may have been inferred from degradation levels
VD	Very dissimilar match with site report (e.g., "acidic" vs. pH > 7)
ND	No national data
NR	pH/acidity or degradation/preservation levels not mentioned in site report

Table A3. Soil description.

VS	Very close match with soil properties reported in site literature; report may have acknowledged map unit, soil association and/or soil series
S	Good match with site report where soil descriptions match well and are likely to indicate the same soil type (soil association, series or type may not have been explicitly addressed but can be inferred)
N	Neutral—conflicting evidence within site report; may include/omit certain soil types and properties; descriptions of soil in site report but unclear what soil type they belong to; neither agrees nor disagrees with national data
D	Poor match with site report where soils descriptions do not match well and are likely to indicate an alternative soil type (soil association, series or type may not have been explicitly addressed but can be inferred)
VD	Clear disagreement with site report; report may have mentioned different soil association or soil type
ND	No national data
NR	Soil information not mentioned in site report

Table A4. Coastal erosion (NCCA). Similarity ranking only conducted on sites with reports of coastal erosion.

VS	Shoreline changes correlate well with areas of erosion identified in site reports
S	General recognition of past erosion across site but areas or severity may not fully align
N	Areas of erosion recognised but do not match well with site reports
D	No changes identified in areas of reported erosion
VD	Areas of accretion mapped in areas of reported erosion
ND	No national data (area of coastline not mapped)
NR	Coastal erosion not mentioned in site report

Table A5. Coastal erosion (CESM). Similarity ranking only conducted on sites with reports of coastal erosion.

VS	Degree of susceptibility correlates very strongly with shoreline changes identified in site report (e.g., Very High/High susceptibility in areas of extensive erosion)
S	Degree of susceptibility correlates well but slightly over/underestimates the severity (e.g., Medium susceptibility in areas of extensive erosion); areas may not fully align
N	Erosion susceptibility acknowledged but specific areas do not align well with site report
D	Degree of susceptibility does not match well with site report (e.g., Low susceptibility in areas of extensive erosion)
VD	Degree of susceptibility vastly different from site report (e.g., Very Low susceptibility in areas of extensive erosion)
ND	No national data (area of coastline not mapped)
NR	Coastal erosion not mentioned in site report

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5. Research Paper 2

A process of elimination? Reviewing the fragmented settlement record of eastern Pictland and its implications for future research

Reid, V. 2021. 'A process of elimination? Reviewing the fragmented settlement record of eastern Pictland and its implications for future research'. Medieval Settlement Research 36: 49–60.

This review paper builds on the results presented in Chapter 4 (Reid and Milek 2021) by synthesising the impacts that major preservation factors have had on the survival of early medieval remains and exploring how they are likely to have influenced interpretations of the Pictish settlement record (RQ *iii*; Chapter 1, section 1.3). It questions the extent to which settlement evidence has indeed been eliminated and whether its archaeological invisibility is solely the result of post-depositional factors. The paper then combines these factors in a discussion on climate change and how changing preservation potentials are likely to impact sites in the future (RQ *ii*). Most significantly, the study highlights important gaps in our knowledge which can be addressed if we approach these sites with specific questions, and provides suggestions of the techniques and strategies that can be employed. This includes site-based geoarchaeological work and embedding these practices more widely into the archaeological sector. This research was awarded the John Hurst Memorial Prize by the Medieval Settlement Research Group in December 2020 and published in the journal *Medieval Settlement Research*.

As the sole author of this paper, I was responsible for the conceptualisation, research design, data collection, visualisation, and the interpretation of the results. I wrote the first full draft of the paper and corrected subsequent drafts based on comments by supervisor Karen Milek and an anonymous journal reviewer. An author-approved manuscript has been deposited in the Durham Research Online (DRO) repository and the journal's embargo will be lifted in October 2023.

Medieval Settlement Research **36** (2021), 49–60

JOHN HURST MEMORIAL PRIZE 2020

In 2004, the Medieval Settlement Research Group announced the launch of a prize, set up in honour of the late John Hurst, who did so much to promote the field of medieval archaeology and in particular the study of medieval settlement. This annual prize of £200 is intended to encourage new and young scholars in the field. Originally a prize for the best master's dissertation, since 2018 the prize comprises a competition for the best student presentation at the MSRG winter seminar on any theme in the field of medieval settlement in Britain, Ireland and the rest of Europe (*c*. AD 400–1600). For the 2020 award, we are delighted to announce that the prize winner is Vanessa Reid, a PhD student at the Department of Archaeology, Durham University. Her PhD research, *Geoarchaeological Approaches to Pictish Settlement Sites: Assessing Heritage at Risk*, is jointly supervised by Dr Karen Milek, Prof. Robin Coningham and Prof. Ian Simpson. It is funded by the NERC's IAPETUS Doctoral Training Partnership alongside a CASE partnership with Historic Environment Scotland.

A PROCESS OF ELIMINATION? REVIEWING THE FRAGMENTED SETTLEMENT RECORD OF EASTERN PICTLAND AND ITS IMPLICATIONS FOR FUTURE RESEARCH

By VANESSA REID[1]

Introduction

Investigation into Scotland's early medieval past has accelerated dramatically in recent decades. The period, roughly defined as AD 300–900, has advanced from having an almost exclusively fortified record to a much broader range of site types spread across a variety of environmental settings. As with much of early medieval Britain, documentary sources are rare, with few native accounts or historical records that pre-date the twelfth century (Noble *et al*. 2013, 1136; Evans 2019). Archaeology has therefore proven essential in developing our understanding of the period and continues to be the key tool in the identification and analysis of early medieval settlement.

Yet despite a series of new discoveries, the size and number of settlement excavations remains relatively slight in comparison with other periods. Unenclosed settlement, and structures in general, have proven particularly elusive, meaning that trends and relationships between site types are difficult to determine and our understanding of the broader economic, social and political spheres in which these sites operated is still very limited. This is particularly pronounced across eastern Scotland, an area that principally lies between the Moray Firth in the north and the Firth of Forth in the south (Walker *et al*. 1982, 1). Many researchers have argued that this area encompasses core Pictish territories, and the majority of new settlement evidence has been identified in this region (Woolf 2006; Carver 2019, 27) (Figure 1). However, the type and nature of remains varies widely, producing a complex and often muddied record that continues to suffer from a lack of robust structural or dating evidence.

A key issue has been the preservation of settlement remains. The stone-built tradition that has resulted in the survival of upstanding structures on the Western and Northern Isles is not typically found across the mainland. Instead, buildings appear to have been constructed from more organic materials, such as turf, earth or timber wattle, with few earthfast elements, and it is likely that much of the evidence of construction has survived very poorly in the ground (Dunwell and Ralston 2008a, 140; Noble *et al*. 2020, 320). Post-depositional events (such as human reuse, animal activity and landscape changes resulting from agriculture, forestry and urbanisation) have further served to disturb remains, often resulting in heavily truncated sites with few artefacts and little to no stratigraphic detail. Although these issues are widely acknowledged, detailed site-based characterisations or broader assessments of the impact of post-depositional factors on the Pictish settlement record have yet to be undertaken. As such, interpretations of the evidence often rely on assumptions about the preservation environment, and there is an uncomfortable trend in which we are gaining an increasing number of sites but little development in our understanding of their formation, role or depositional histories. The result is that significant aspects of the settlement record, in particular domestic dwellings and unenclosed sites, continue to be left out of important syntheses (for example, Blackwell 2019; Noble and Evans 2019). If early medieval Scotland is to continue its meaningful contribution to wider British and European narratives, such issues require addressing.

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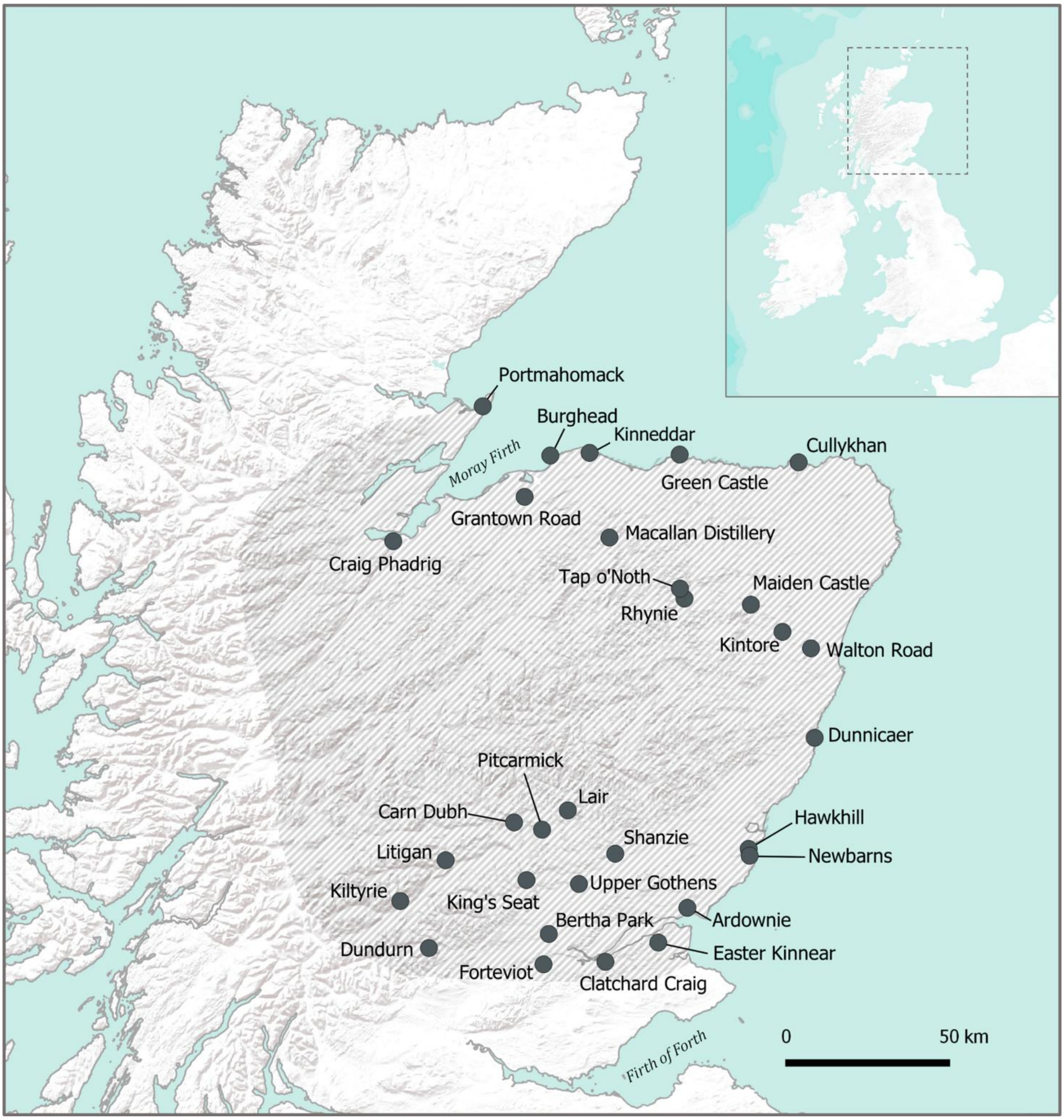

Figure 1 Eastern Pictland (shaded) in relation to the UK, with location of key settlement sites mentioned in-text. Base map: ESRI 2020 (Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community).

Scope and Methodology

Reliable interpretations depend on a clear understanding of the processes that have affected formation and influence the preservation of archaeological sites (Schiffer 1983; 1985; 1987; Shahack-Gross 2017). By reviewing both published excavation reports and grey literature pertaining to 30 sites with structural evidence of early medieval settlement, this paper synthesises the impacts that major preservation factors have had on the survival of early medieval remains and considers their influence on our interpretation of the Pictish record. It complements analysis conducted by Reid and Milek (2021) that characterises the type of post-depositional processes most likely to affect eastern Scotland's early medieval record and the frequency with which they are identified on-site.

The sites mentioned in this study (Figure 1; Table 1) comprise the major settlement evidence for eastern Pictland and cover a range of different environmental contexts, providing a strong representation of the impacts most likely to occur at site-level. However, owing to some restrictions on the accessibility of grey literature, the study is not exhaustive and the relatively small number of identified sites (in comparison to other periods) means that we may be missing crucial examples of preservation impacts. Similarly, it should be noted that the factors mentioned in this study are not the exclusive determinants of the destruction or survival of archaeological material. Their inclusion is based on what has been identified during archaeological inquiry, which is the product of a number of methodological biases that include the scale and nature of an investigation and the techniques of analysis used. For example, there was no exploration of deposit redox potential in the site literature, despite its role in determining the destruction of organic remains. There is also an overwhelming bias in favour of modern rural settings, as almost no early medieval structural evidence has been found in urban contexts. As such, the impact of urban development on the survival of the Pictish record almost certainly merits further consideration but is outwith the scope of this paper. Nevertheless, efforts to connect major issues affecting the survival and quality of the early medieval record have been virtually non-existent and this paper provides a much-needed synthesis that should encourage further research. In initiating this process, the study looks towards the future of these sites and considers what techniques and strategies we may use to try and overcome the current stalemate.

Factors influencing preservation

Reuse

The reuse of a structure, either for habitation or other purposes, can result in the formation of new deposits and the truncation, removal or reworking of existing ones (Schiffer 1985; Rothschild *et al.* 1993; LaMotta

Table 1 Key settlement sites mentioned in-text.

Site	Grid reference	Reference
Ardownie	NO 4948 3379	Anderson and Rees 2006
Bertha Park	NO 07316 26583	Engl 2020
Burghead	NJ 1090 6914	Edwards and Ralston 1978
Carn Dubh	NN 976 605	Rideout 1995
Clatchard Craig	NO 2435 1780	Close-Brooks 1986
Craig Phadrig	NH 6400 4527	Peteranna and Birch 2019
Cullykhan	NJ 8373 6621	Greig 1971
Dundurn	NN 7080 2327	Alcock *et al.* 1989
Dunnicaer	NO 8821 8464	Noble *et al.* 2020
Easter Kinnear	NO 40519 23382	Driscoll 1997
Forteviot	NO 05507 17393	Campbell and Driscoll 2020
Grantown Road	NJ 03080 57200	Cook 2016
Green Castle	NJ 4885 6877	Ralston 1987
Hawkhill	NO 6820 5140	Rees 2009
Kiltyrie	NN 62550 37761	Atkinson 2016
King's Seat	NO 0093 4303	MacIver and Cook 2017; 2018; 2019
Kinneddar	NJ 2243 6969	Noble, Cruikshanks *et al.* 2019
Kintore	NJ 78739 16232	Cook and Dunbar 2008
Lair	NO 1387 6376	Strachan *et al.* 2019
Litigan	NN 7666 4966	Taylor 1990
Macallan Distillery	NJ 27825 44715	Dunbar 2017
Maiden Castle	NJ 6942 2435	Cook 2011
Newbarns	NO 68474 49352	McGill 2004
Pitcarmick	NO 0598 5812	Carver *et al.* 2012
Portmahomack	NH 91485 84020	Carver 2016
Rhynie	NJ 4974 2634	Noble, Gondek *et al.* 2019
Shanzie	NO 2791 5045	Coleman and Hunter 2002
Tap o'Noth	NJ 4845 2930	O'Driscoll 2020
Upper Gothens	NO 1677 4152	Barclay 2001
Walton Road	NJ 872 113	Woodley 2018

and Schiffer 1999). Several mainland sites, such as Portmahomack monastery and the 'scooped' structures at Easter Kinnear, show significant episodes of redevelopment within the early medieval period that have simultaneously provided key insights into settlement activity and restricted more detailed interpretations. For example, occupation at Dunnicaer promontory fort is defined by multiple successive hearths and postholes across very small areas, suggesting that buildings were frequently constructed, reworked, demolished and rebuilt (Noble *et al*. 2020, 320). However, this intense activity, coupled with additional truncating processes such as agriculture and stone-robbing, has also meant that establishing whether the buildings functioned as residences, workshops or more specialised buildings (or had indeed changed function throughout their lifecycles) has so far proved impossible (Noble *et al*. 2020, 320).

A number of sites also attest to the reuse of Pictish settlement in later periods (e.g. Kiltyrie, Kinneddar and Pitcarmick), introducing questions over the longevity of structures and to what extent they may have persisted in a habitable or reworkable state. A common assumption is that the organic building materials used across mainland sites would have quickly degenerated or been undermined by animal burrowing (Dunwell and Trout 1999; Walker 2006). Yet, the medieval reuse at Pitcarmick occurred up to 300 years after initial construction, suggesting that structures could have survived in some measure for 200–300 years (Carver *et al*. 2012, 186). However, patterns in this reuse, and the longevity of Scotland's early medieval settlements in general, are still largely unclear due to a relatively small dataset and incomplete dating evidence.

The fact that we still have no clear definition of what constitutes a Pictish house, and little understanding of the reuse or lifecycle of structures, means that recognising evidence of Pictish settlement in the east continues to prove a challenge. It is increasingly likely that evidence of early medieval occupation has been missed during the survey and excavation of other settlement sites, where secondary or tertiary occupation events are 'masking' or have removed structural indicators of Pictish activity. It is also a distinct possibility that, even when early medieval dates have been reported, they have not been fully explored or have been dismissed on account of suspected contamination: for example, in structural forms that are seemingly atypical of the period. This has been the case in Moray, where late first-millennium AD dates from two separate groups of roundhouse structures have been heavily questioned on account of having no obvious parallels (see Cook 2016 and Dunbar 2017 for further discussion).

However, the reuse of pre-existing settlement by early medieval people also has significant implications for our interpretation of the record. Across the western and northern parts of the country, patterns of reoccupation and redevelopment have been considered a key element of transition and are likely to hold vital information as to the varied structures across the Firthland regions and for the shift from round to rectangular house forms in general (Carver 2019, 187–188). There is certainly widespread evidence for the reuse of Iron Age hillforts and the more ephemeral reuse of Iron Age souterrains (see Harding 2009, 184 for discussion on the relationship between souterrains and 'scooped' structures in Pictland), and in areas where aspects of the early medieval record continue to elude researchers, the re-evaluation of Iron Age sites should be an important consideration. Recent excavations at Tap o'Noth in Aberdeenshire – a vitrified Iron Age fort with a dense concentration of over 800 supposed Bronze or Iron Age hut platforms – have highlighted the potential of this approach. Though investigation of the inner fort failed to produce any evidence of early medieval reuse, excavation of the outer fort (including two of the hut platforms) unexpectedly returned third- to sixth-century AD dates (O'Driscoll 2020). Pictish-period dwellings in Aberdeenshire are very rare and if future investigation supported these findings, the site would stand as the one of the largest forts and native settlements across Britain and northwest Europe, completely rewriting the narrative of early medieval settlement in Scotland (O'Driscoll 2020).

It is also important to look beyond the direct adaption or reoccupation of existing structures when attempting to locate and understand the settlement record. It has been recognised that early medieval royal sites across northern Britain and Ireland are commonly associated with prehistoric ritual landscapes, and this would certainly seem to be the case with high-status Pictish sites such as Rhynie and Forteviot (Foster 2014, 59–60). However, as new surveys and radiocarbon dates contribute to the narrative, it has become increasingly apparent that we should extend our awareness of this trend to more 'low-status' sites. The best preserved early medieval buildings on the mainland – farmstead structures in the unenclosed settlements of upland Perthshire – were only discovered during the intensive survey of multi-period landscapes (RCAHMS 1990). It may therefore be the case that the 'masking' of settlement amongst more prominent remains has contributed to the relatively low number of unenclosed sites recognised in other parts of the country. Given that we cannot rely on a single architectural form to direct our identification of settlement, exploring the wider landscape setting may prove to be a fruitful endeavour.

Agriculture

Numerous surveys and experimental work have recognised agriculture to be the most significant threat to the UK's archaeological record. The study by Reid and Milek (2021, 736) found that over 80% of early medieval sites in eastern Scotland had been affected by agricultural practices, with impacts ranging from the truncation and scarring of archaeological deposits to the physical fragmentation and chemical deterioration of artefacts (see Table 2).

Where it is identified on Pictish sites, the most severe cases of truncation typically result from repeated episodes of modern ploughing and thus predominantly affect sites in the arable lowlands. At Newbarns in Angus, excavation of an unenclosed rectilinear structure revealed that the average surviving depth of excavated features was around 0.2m, with some deposits as shallow as 0.02m (McGill 2004). Given that repeated ploughing can truncate sites by 0.07–0.1m over a 30-year period (Oxford Archaeology 2010, 17–18), it is unsurprising that obliteration as a result of modern ploughing is one of the theories put forward for the general lack of early medieval settlement observed across mainland Scotland (see Dunwell and Ralston 2008a).

However, the rate at which site truncation occurs is dependent on a multitude of factors that include the depth and frequency of cultivation, crop type, and environmental conditions such as soil type, drainage and topography. Processes that remove soil from agricultural land (e.g. windborne or waterborne erosion) or compact the soil (e.g. heavy machinery and livestock) effectively bring buried archaeology closer to the zone of erasure and accelerate this process. Yet the extent to which this threatens, or has already affected, Scotland's archaeology is almost unknown. Very few studies have attempted to identify compaction or erosion in relation to archaeological sites (see Dunwell and Ralston 2008b), and much of what we know more generally about erosion rates on agricultural land in Scotland comes from just a handful of individual studies (Lilley *et al*. 2018). It is clear that further investigation is required.

Nevertheless, ploughing has had a very obvious impact across eastern Scotland's early medieval record and remains a possible explanation for the limited recovery of internal or occupation deposits in extant structures (Cook 2016; Dunbar 2017). Yet a number of cases challenge the scale at which we can apply this assumption and the reality may be more nuanced. Sites in upland environments that lie above the altitudinal limits of intensive cultivation (e.g. Carn Dubh and Lair) also present with a lack of robust stratigraphy, as well as lowland structures with a 'scooped' component that lies considerably beneath the ploughzone (e.g. Easter Kinnear). In these cases, potential reasons for the lack of internal deposits could include the reworking of deposits by soil biota (see *Bioturbation* below) or anthropogenic factors, such as maintenance practices or the use of floor coverings (see Gé *et al*. 1993, 155–156; Boivin 2000; Macphail and Goldberg 2010, 598–599; 2018, 226–234).

Bioturbation

The disruption of sedimentary deposits by roots, invertebrates and animals has been widely identified across early medieval sites but to date has prompted little supplementary investigation. The majority of known cases relate to the truncation of features or the blurring of stratigraphic boundaries by plants and mammals, likely due to the ease with which their roots and burrows can be identified during excavation. Where it has been conducted, bulk analysis has also been successful in identifying the contamination of deposits with external material such as insect eggs, insect remains, and plant roots and seeds (e.g. Carn Dubh, Macallan Distillery). Combined, the activity of these organisms can result in a heavily disturbed record that limits the availability of secure dating evidence, making interpretations about individual structural form or settlement history problematic.

In looking for an explanation as to the general lack of interior stratigraphy found across eastern sites, bioturbation merits further consideration. Soft building materials such as turf and earthworks are highly susceptible to intrusion by burrowing mammals and introduce an abundance of organic material that, in the right soil environments, can be quickly turned over by soil biota (Dunwell and Trout 1999). Root and animal activity could therefore result in the mixing of collapsed roof, wall and floor deposits into what are seemingly homogeneous layers, particularly in sites that have degenerated upstanding remains or are located on soils that have a looser, more easily penetrated structure (e.g. sandy subsoils). This was certainly the case at Kintore where, in a structure with limited floor layers, micromorphology identified bioturbation to be the most significant factor in destroying the internal fabric, alongside weathering and compaction (Ellis 2008).

However, the detailed investigation of soil processes on Pictish settlement sites is rare and there are many contexts where such analysis has not been conducted. Upland settlement, for example, has had no published micromorphological analysis to confirm or deny the impact of bioturbation on internal deposits, despite agriculture and reuse providing inadequate explanations for this occurrence. There has also been virtually no application in sites with limited or suspect dating evidence (e.g. Grantown Road and Macallan Distillery), which is surprising given that the impact of primary bioturbators, such as earthworms, is largely recognised through thin-section analysis and may be missed if such techniques are not routinely employed (Stein 1983; Taylor 2019).

Perhaps of greater significance has been the identification that, in the medieval burials and platform at Hawkhill in Angus, bioturbation occurred relatively recently and may have still been taking place at the time of excavation (Guttman 2009). Where stratigraphy is not observable to the naked eye, it may still be detectable in thin-section, but the opportunity to access this information is waning. In areas where ploughsoil thinning, excavation or erosion are making sites more susceptible to intrusion, this imposes a significant time pressure and the potential loss of valuable deposits if adequate steps are not taken to recover information (Church 2009, 45).

Soil acidity

The majority of Scotland's soils are naturally acidic and are considered to be the primary reason for the lack of organic materials and artefacts recovered from Pictish settlement sites (Taylor 1990, 38; Noble *et al*. 2020, 302). Bone, teeth and shell degrade (and are eventually destroyed) most rapidly in environments where the soil water is acidic and unsaturated, for example in soils that are wet, free-draining and formed on sands or acidic parent materials (Kibblewhite *et al*. 2015, 250). These conditions dominate eastern Scotland's arable lowlands and, when coupled with the physical fragmentation and disturbance that results from cultivation, it is unsurprising that very few artefacts survive in these contexts. The microbial activity that degrades organic matter, such as plant material, fungal spores and insects, is similarly accelerated by tillage disturbance, resulting in the extremely poor recovery of environmental evidence at sites such as Upper Gothens, which reported just a single, badly preserved cereal grain (Barclay

Table 2 Major preservation impacts identified during excavation of Pictish settlement, with examples of the affected sites in eastern Scotland.

Factors Affecting Preservation	Recognised Impacts across Pictish Sites	Examples of Affected Sites
Reuse	<u>Reuse of Pictish settlements</u> • Loss of structural form via alteration of structures (inc. reuse of building materials and stone-robbing events) • Truncation, removal and/or reworking of internal deposits • Formation of new deposits • 'Masking' evidence of early medieval activity, via: – the greater prominence of medieval (or later) structures in the landscape – more intense reuse in medieval period (or later)	Burghead, Carn Dubh, Craig Phadrig, Dunnicaer Easter Kinnear, Kiltyrie, King's Seat, Kinneddar, Litigan, Maiden Castle, Pitcarmick, Portmahomack
	<u>Reuse of pre-existing settlement during Pictish period</u> • Alteration of structures (inc. reuse of building materials) • Reworking and commingling of deposits • Incorporation of new settlement into prehistoric landscapes • 'Masking' evidence of early medieval activity, via: – the greater prominence of prehistoric stone structures in the landscape – assumptions over dates of sites based on structural form – more ephemeral reuse in early medieval period	Ardownie, Bertha Park, Carn Dubh, Craig Phadrig, Cullykhan, Hawkhill, Lair, Shanzie, Tap o'Noth, Walton Road
Agricultural attrition	<u>Ploughing (medieval, post-medieval and modern)</u> • Destruction, truncation and scarring of archaeology • Reworking of deposits and loss of stratigraphic boundaries • Horizontal and/or vertical displacement of artefacts • Physical and chemical degradation of artefacts • Compaction of soil (over time results in the effective deepening of cultivation) • Increased susceptibility of exposed archaeological deposits to wind-borne erosion	Ardownie, Dunnicaer, Easter Kinnear, Grantown Road, Hawkhill, Kiltyrie, King's Seat, Kinneddar, Kintore, Lair, Macallan Distillery, Newbarns, Portmahomack, Rhynie, Walton Road

Agricultural attrition	Ancillary activities (e.g. subsoiling, insertion of field drains etc.) • Truncation of archaeology • Compaction of soils via vehicles and heavy machinery	Maiden Castle, Pitcarmick, Upper Gothens
	Animal stocking • Erosion of sites through trampling • Compaction of soil (increases the susceptibility of underlying archaeology to damage and removal if the site then comes under ploughing) • Damage to artefacts/structures • Vertical and/or horizontal displacement of soil and artefacts	Lair, Rhynie
Bioturbation (via roots, invertebrates, mammals)	• Vertical and/or horizontal displacement of sediments and artefacts • Permanent disruption of stratigraphic boundaries • Loss of structural integrity • Damage and fragmentation of artefacts and ecofacts • Contamination of deposits with exogenous material	Carn Dubh, Craig Phadrig, Dunnicaer, Easter Kinnear, Hawkhill, King's Seat, Kintore, Macallan Distillery, Newbarns, Rhynie, Shanzie, Walton Road
Soil acidity	• Chemical degradation and/or destruction of artefacts and ecofacts (e.g. bone, teeth, shell, iron) • Loss of environmental evidence and organic material (e.g. wood, insect remains, soft tissues) • Potential influence in pedogenic processes, resulting in the movement of fine material and homogenisation of deposits	Dundurn, Dunnicaer, Easter Kinnear, Litigan, Macallan Distillery, Pitcarmick
Coastal erosion	• Loss and truncation of archaeological deposits, features and structures • Exposure of archaeological deposits and structures resulting in increased susceptibility to physical and chemical deterioration by the elements	Burghead, Dunnicaer, Green Castle (Portknockie)

2001, 43; Kibblewhite *et al*. 2015, 250). The organic-rich peaty soils of the uplands typically have acidic pH values below 5, often below 4, and equally return limited quantities of bones, teeth and organic material (Paterson 2011, 15).

Metal artefacts, and the associated evidence of metalworking (e.g. slag and moulds), have fared somewhat better and provide the majority of our knowledge of manufacturing and settlement activity. The most significant evidence comes from hoards such as Gaulcross and Norrie's Law, but these have been found in isolation and contextualised examples are almost exclusively limited to enclosed, high-status sites such as Rhynie, Clatchard Craig, King's Seat and Dundurn (Blackwell and Goldberg 2019). More ephemeral evidence in the form of slag and revetted platforms have been identified in unenclosed settings (e.g. Hawkhill in Angus) but again there is little accompanying context and our understanding of manufacturing within the Pictish period remains heavily skewed towards concepts of status and/or ritual. In general, the artefact record from unenclosed sites is scant, with just a handful of heavily corroded iron and decaying stone objects recovered from sites such as Lair and Easter Kinnear.

It is important to note that this absence of material in unenclosed sites does not necessarily reflect an impoverished lifestyle – in fact, excavators are often careful to avoid such interpretations (see Atkinson 2016, 77). The most common domestic artefacts are likely to have been made of wood and thus their destruction in the acidic soils of eastern Scotland is expected (Laing 2006, 76). However, as with bioturbation, very few studies have actually engaged with pH assessments at the site level, meaning interpretations regarding the presence or absence of particular artefact types are often based on assumptions about the preservation environment, rather than confirmed findings. Being unable to account for these processes at the site level means we may be missing important information over the reuse of objects, the types of materials used, or the function of settlements in general.

Soil pH is also known to influence soil-forming processes and may be linked to the seemingly homogeneous deposits reported across Pictish settlement sites. Acidic conditions promote the dispersion of fine organo-mineral material from archaeological sediments and underlying soils, which is carried down the soil profile by rainwater. In a study of archaeological deposits at the Viking Age settlement of Kaupang in Norway, Milek and French (2007) identified this as one of the post-depositional processes responsible for the generally poor preservation of artefacts, bones and sediments, alongside leaching, bioturbation and the redistribution of iron. Combined, these had a cumulative effect in which the chemistry, structure and colour of the original occupation deposits were altered to such an extent that the sediments were rendered almost uniform in appearance and composition (Milek and French 2007, 324–325). Given the lack of stratigraphy observed across Pictish settlement, examination of these processes in conjunction with pH analysis is likely to offer much needed detail.

Coastal erosion

The destructive nature of coastal erosion is well known and has impacted (and continues to impact) key sites across eastern Pictland. A dramatic example can be found

Figure 2 Erosion at Dunnicaer (top left – aerial view showing erosion foot at right side of stack; bottom left – mainland-side erosion face; right – proximity of surviving hearth to erosion edge in lower terrace). Top left created with Google Earth 2021 / photographs author's own.

at Dunnicaer promontory fort, where erosion has caused the headland to become detached from the mainland and resulted in the partial and total loss of structural elements (Figure 2; Noble *et al.* 2020). Estimating the total area lost has proven difficult; however, a footprint of eroded rock indicates that the site was likely to have been at least 60m longer and up to 25m wider than its current extent (although additional estimations have been more generous – Noble *et al.* 2020, 309). Where the loss of a site has been so extensive, considering the potential role coastal erosion has played throughout the site's history is vital to the interpretation of its archaeological remains. The intense rebuilding activity identified within the surviving portion of Dunnicaer fort (see *Reuse* above) has been interpreted as a response to rapid expansion within a limited space that was possibly exacerbated by the effects of contemporary coastal erosion (Noble and MacIver 2017, 32). This is an important reminder that destructive agents do not exclusively occur following abandonment.

As at Dunnicaer, erosion at Burghead promontory fort in Moray is ongoing with approximately 7.9m of erosion having occurred on the northwest side of the site since 1904 (of which over 2.5m occurred between 1976 and 2011 alone: Noble *et al.* 2018, 34). Land loss is clearly accelerating, and recent excavations demonstrated that the best-preserved stretches of rampart are those most under threat, with some areas surviving just one metre from a major erosion face (Noble *et al.* 2018, 34). It is therefore clear that coastal promontory forts face severe threat from erosion. However, the majority of these site types in eastern Scotland remain undated, meaning that the extent to which this process has impacted the early medieval settlement record as a whole remains uncertain.

The threat of climate change

What links these processes, aside from their negative impact on the survival of the archaeological record, are predictions that their rate of destruction will increase in the coming decades and centuries. Climate change in Scotland has been characterised by increasing temperatures, altered patterns of precipitation, and more frequent extreme weather events that have already had dramatic effects on our natural and cultural environment (Harkin *et al.* 2017, 4). Though the impact on coastal heritage has long been acknowledged, recent years have seen a more focused awareness that this threat extends to all heritage assets, including inland and buried remains (Harkin *et al.* 2017; Harkin *et al.* 2019).

In agricultural zones, waterborne erosion and soil compaction (which effectively brings archaeology closer to the plough and can require deep and invasive remedial operations such as subsoiling or pan-busting) are major concerns (Oxford Archaeology 2002, 6–7). These factors are exacerbated by wet conditions and are likely to become a more significant problem as Scotland is subjected to wetter autumns/winters, and more erratic and extreme rainfall events (Troldborg *et al.* 2013; Lilly *et al.* 2018, 13). This threat is furthered by the fact that eastern Scotland accounts for over 65% of the country's potato crops, a type of cultivation that already requires deep ploughing and more intensive soil preparation (Oxford Archaeology 2002, 13). Current trends also indicate that the extent of planted agricultural land is set to increase further in coming years (RESAS 2019).

Changes to soil chemistry are expected to arise from increased temperatures and episodes of prolonged rainfall, altering the preservation potential of sites and buried remains (Harkin *et al.* 2019). Increased concentrations of atmospheric carbon dioxide have already been linked to greater microbial activity, whilst extreme dry spells have the potential to desiccate the very few examples of waterlogged deposits that have been identified at sites such as Portmahomack and Dundurn hillfort (Alcock *et al.* 1989; Spall 2007; EEA 2012, 150; Harkin *et al.* 2019, 32–34). Rates of bioturbation are also expected to increase because of longer growing seasons that encourage the spread of new and invasive species, and deeper and more penetrative root growth (Harkin *et al.* 2019, 33). Combined, these processes will result in the increased truncation of archaeological sites and the accelerated decay of artefacts and environmental evidence, further diminishing an already limited resource (Harkin *et al.* 2019, 34).

Moving forward

Rather than lamenting this potential loss, recognition of these processes should encourage a review of the techniques and methods we use to investigate Pictish settlement sites. There is an increasing awareness that preservation *in situ* may not always be the most suitable strategy of care and, in situations where negative conditions cannot be halted or significantly impeded, excavation is now being promoted as an active management plan (Harkin *et al.* 2019).

The first step in ensuring this approach is successful is to develop a baseline understanding of the current factors affecting preservation. This paper has outlined a number of major impacts but has also highlighted the need for more detailed site-based characterisations of the preservation environment and the post-depositional processes that have contributed to its current state. To address these gaps, archaeological analysis would benefit from a wider integration of techniques that are specifically designed to answer these questions. This could include geoarchaeological methods such as micromorphology, which is able to identify processes such as leaching, bioturbation and maintenance practices, and has consistently proved itself to have the greatest interpretative power of any single technique (Milek and Roberts 2013, 1845). Analysis of soil pH will also be useful in confirming the presence/absence of material types at the site level, whilst multi-element analysis and magnetic susceptibility (an indication of burning and minerogenic variability) could offer new insight into activity areas and the spatial organisation of structures.

Results from these types of investigation will undoubtedly be beneficial for the reconstruction of individual site histories but also have the potential to inform much broader research agendas and management strategies if compared across a range of site types and environmental settings. Understanding how site location and different building materials influence the preservation of early medieval settlement is essential in identifying sites most at risk of destruction or, alternatively, targeting those that have the best examples of preservation. Similarly, it encourages an examination of the relationship between archaeology, land use, animal activity and soil properties, which will benefit our interpretation of the archaeological record far beyond eastern Pictland.

Integration of these methodologies and results in government and planning policy will be the key to meaningful action across the archaeological landscape. On agricultural land, scheduled monuments are currently protected through the Ancient Monuments (Class Consents) (Scotland) Order 1996, which limits damaging land use strategies but cannot control agricultural practices if they are shown to have occurred on the land within the previous ten years (UK Government 1996). This means that ploughing can occur at a consistent depth even when ploughsoil thinning is observed. Winter cover crops (which are planted to cover soil rather than be harvested) can help to limit waterborne erosion from bare soil in winter storms and heavy rain, and reduce snow compaction of topsoil horizons, essentially acting as soil armour for buried sites (Acuña and Villamil 2014). Many farmers have been put off the practice by the expense and extra effort involved in establishing cover crops; however, the threat of climate change has encouraged a review of its benefits, with trials in eastern Scotland looking to using cover crops to build soil structure and mitigate the effects of extreme weather events (FFBC 2020). Should the benefits to archaeological sites be included in such trials, these practices could be written into new policy or recommended in cases where known archaeological sites are situated on regularly worked agricultural land.

Another strategy would be to embed dedicated geoarchaeological work and assessments of the preservation environment into developer-funded investigation. This type of excavation offers a prime opportunity to gain comparative empirical data across a wide range of sites, which can be used to inform broader heritage management strategies. Currently, there is no system in place to initiate this process, as Scotland lacks both the equivalent of Historic England's Science Advisors (who provide support and advice to local authorities determining planning applications) and any national guidelines on the application of geoarchaeology.

Conclusions

By reviewing the site-based evidence held in excavation reports, this study has identified a number of major factors that have affected the preservation of early medieval remains in eastern Scotland and influenced their interpretation. Widespread agricultural attrition, bioturbation, aggressive soil conditions and coastal erosion have resulted in a heavily truncated record that restricts our access to more detailed assessments of settlement form and function. The reuse of structures, both during early medieval occupation and following its abandonment, has also caused interpretational issues but may offer a new avenue of investigation when considering the potential location of settlement activity. Perhaps most significantly, this study has highlighted important gaps in our knowledge which can be addressed if we approach these sites with specific questions about the preservation environment, rather than attempting to address them following excavation. Finally, the threat posed by each of these processes cannot be understated and as climate change is set to accelerate their rate of destruction, the way we approach the archaeological record becomes vitally important.

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6. Research Paper 3

Revealing the invisible floor: Integrated geoarchaeological analyses of ephemeral occupation surfaces at an early medieval farmhouse in upland Perthshire, Scotland

Vanessa Reid, Karen Milek, Charlotte O'Brien, David Sneddon and David Strachan
(submitted to Journal of Archaeological Science)

This case study addresses questions posed in Chapters 4 and 5 regarding the application of geoarchaeological techniques to the assessment of preservation factors in poorly preserved sites (see also RQ *i, iii, v and vii*; Chapter 1, section 1.3). It presents a comparative study of multiple geoarchaeological methods that are used to investigate ephemeral occupation surfaces in a 7th to 9th century AD turf longhouse in the upland settlement of Lair in Glen Shee, Perthshire. Techniques include microrefuse analysis, pH, electrical conductivity, loss-on-ignition, magnetic susceptibility, multi-element analysis by pXRF, and micromorphological analysis. Poorly defined occupation surfaces restrict the ability to interpret the use of space in archaeological structures and settlements around the world, and thus this paper demonstrates a theoretical and methodological protocol that can be applied globally. This research has been submitted to the *Journal of Archaeological Science* and is currently awaiting review.

The concept and methodology of this paper were developed in partnership with co-author Karen Milek (primary supervisor to this thesis). As the first author of this paper, I was responsible for the on-site sampling, laboratory analyses, data collection, statistical data analyses, visualisation, and the interpretation of the results. I wrote the first full draft of the paper and corrected subsequent drafts based on comments by the co-authors. Charlotte O'Brien conducted the charcoal identifications presented in the micromorphological analysis; David Strachan was the site director at Lair; and David Sneddon was a lead excavator who provided the archive material and supporting documents which aided site analysis. All authors read and agreed to this version of the manuscript prior to submission.

Revealing the invisible floor: Integrated geoarchaeological analyses of ephemeral occupation surfaces at an early medieval farmhouse in upland Perthshire, Scotland

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Abstract

Poorly defined occupation surfaces restrict the ability to interpret the use of space in archaeological structures and settlements around the world. Integrated geoarchaeological methods, such as soil chemistry and micromorphology, can provide information about site preservation and characterise the use of archaeological space when stratigraphy is lacking, but have rarely been applied in such contexts. This paper presents a comparative study of multiple geoarchaeological methods that were used to study ephemeral occupation surfaces in a 7th to 9th century AD turf longhouse in the upland settlement of Lair in Glen Shee, Perthshire, Scotland. When subjected to principal component analysis (PCA) and k-means clustering, the combined data were successful in identifying activity areas and relating this to maintenance practices, the organisation of space, and post-depositional processes. Most significantly, the integrated approach demonstrated that ephemeral occupation surfaces retain surviving characteristics of the use of space, even if floors are not preserved well enough to be clearly defined in the field or in thin-section.

Keywords

Geoarchaeology, micromorphology, settlement, site formation processes, early medieval

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1. Introduction

Occupation deposits and their associated assemblages are vital resources for interpreting the archaeological record. They provide information on the organisation of space, the types of economic and maintenance activities that governed daily life, and the changes that occurred in these practices during the abandonment or reuse of a structure (Carr 1984; LaMotta and Schiffer 1999; Macphail et al. 2004; Milek 2012). However, these occupation deposits can also be disrupted by numerous natural and cultural processes, resulting in absent, fragmented or poorly defined sequences that continue to restrict archaeological interpretations around the world (Hamerow 2002: 12; Parma et al. 2011; White and Eyre 2011: 62; Zerboni 2013; Grono et al. 2022).

Such problems are routinely encountered in the study of early medieval Scotland (c. AD 300-900; also known as the Pictish period), particularly across mainland areas. Although there have been huge advances in the ability to recognise and date sites, the number of excavated structures is still relatively slight in comparison to other periods and neighbouring areas (Prado and Noble 2022: 1). The vast majority of structures lack definable floor layers and produce few artefacts, and our understanding of daily life or the use, maintenance and organisation of social space remains limited (Driscoll 2011; Reid and Milek 2021). Further complicating interpretations is an absence of studies dedicated to examining the natural and cultural factors that have contributed to this poor preservation (though see Sharples 2012 for exceptions in the Western Isles). Without a clear understanding of the preservation conditions and processes affecting early medieval occupation surfaces in mainland Scotland, reliable interpretations of their settlements will remain elusive.

Geochemistry can provide an effective solution for characterising the use of archaeological space when material records and stratigraphy are lacking. Alongside common residues of bone and charcoal, material deposited by humans and animals leaves behind organic, magnetic and elemental signatures that can be analysed through a variety of soil chemistry techniques (Entwistle et al. 1998, 2000a; Jones et al. 2010; Milek and Roberts 2013; Nielsen and Kristiansen 2014; Mikołajczyk and Milek 2016; Gustavsen et al. 2018). Soil micromorphology – the study of archaeological deposits in thin-section – can also resolve minute lenses of stratigraphy not apparent to the naked eye and provide vital detail about the composition of microstratigraphy, site formation processes, and site preservation conditions (Courty et al. 1989;

Banerjea et al. 2015). Whilst individually these techniques offer unique and valuable information about a site, their interpretational power is dramatically enhanced when integrated into a multi-method dataset (Milek and Roberts 2013). To date, such studies have successfully distinguished different activity zones across a site (Jones et al. 2010; Milek and Roberts 2013), interpreted land-use practices (Entwistle et al. 2000b, 2017) identified organic and inorganic inputs (Shahack-Gross et al. 2005; Shillito et al. 2014; Broderie et al. 2020), characterised floor formation processes (Robertson and Roy 2021) and traced the movement of resources around farmsteads (Smith 1996). They have also proven essential in clarifying post-depositional processes such as bioturbation, leaching and decay, which can alter sediment chemistry and rework stratigraphy (Canti 2003; Milek and French 2007; Banerjea et al. 2015).

To assess the value of these techniques in the study of Scotland's early medieval settlement sites and their elusive occupation surfaces, a dedicated geoarchaeological sampling strategy was conducted on a 7th to 9th century AD turf longhouse (known as Building 3) in the upland settlement of Lair in Glen Shee, Perthshire, Scotland (Fig. 1). The building has some of the best preserved structural remains for the period, however internal deposits were almost impossible to define in the field owing to their thin and seemingly fragmented nature. The distributions of microrefuse and geochemical properties – pH, soluble salt content (electrical conductivity), organic matter (loss-on-ignition), magnetic susceptibility and multiple elements – were subjected to multivariate statistical analysis, mapped across the excavated surface, and compared against each other and the results of micromorphological analysis to generate new information about the depositional and post-depositional history of the site, preservation conditions of the occupation deposits, and, if possible, original activity areas in the building.

2. Study Area

The extant remains at Lair are representative of the rich, multi-period landscapes found not only in Glen Shee, but across eastern and central Scotland. Situated on heather and grass-covered terraces beyond the altitudinal limits of modern intensive agriculture, the Lair complex extends from the valley floor on the west bank of the Shee Water stream and rises 300 m upslope to the abandoned hamlet of Corra-lairig at c. 430 m above sea level (Strachan et al. 2019: 24). The underlying superficial geology consists of glaciofluvial deposits of silt, sand and gravel, while the bedrock geology is of the quartz-rich Mount Blair Psammite and Semipelite Formation (BGS 2022).

The area contains a wide range of post-medieval shielings, bothies and field banks as well as evidence of much earlier activity that includes two early prehistoric cairns, multiple groups of roundhouses, and two clusters of early medieval Pitcarmick-type buildings. The latter are a distinctive monument type found in the Glen Shee and Strathardle areas of Perthshire and are primarily built of turf. They are oblong in shape, range between 10 m and 30 m in length, and have rounded ends (Carver et al. 2012; Strachan et al. 2019: 8).

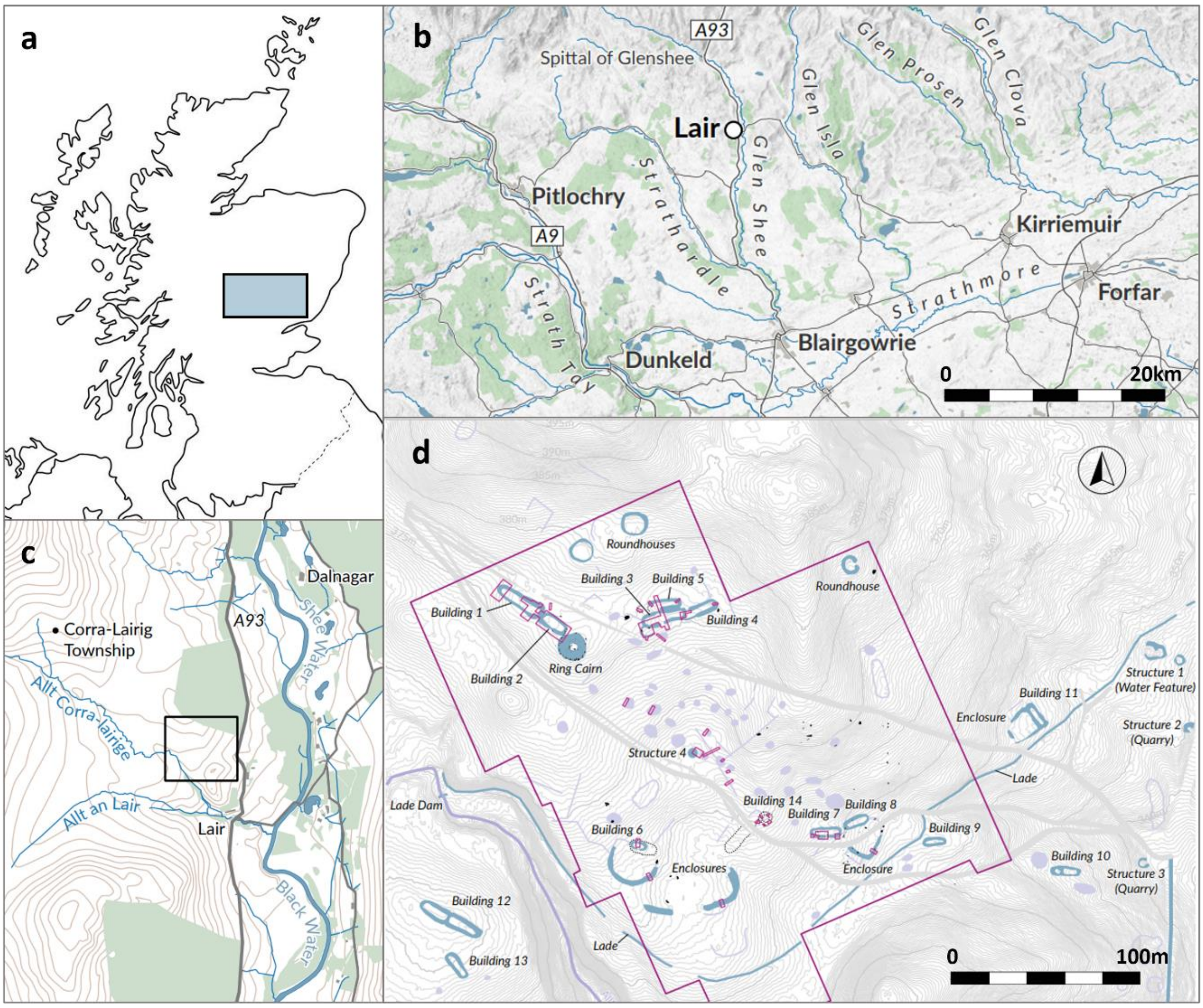

Fig. 1. Location of Lair in relation to (a) Scotland and (b) Perthshire; location of Building 3 in relation to (c) Glen Shee and (d) archaeology and excavation trenches (after Strachan et al. 2019 © PKHT; contains OS Data © Crown copyright and database right 2018, 2022; SRTM, ASTER GDEM is a product of METI and NASA; Imagery GIScience Research Group at Heidelberg University).

Building 3 is situated 370 m above sea level and is the best preserved and most extensively excavated structure amongst a group of three Pitcarmick-type buildings (NO 1392 6377) (Fig. 1; RCAHMS 1990: 150). The remains of turf and earth walls had degraded to form banks that spread up to 2 m in width and 0.4 m in height, with the overall plan of the structure measuring 23 m in length, with a width that varied from 6.5 m in the west end to 4.5 m in the east end (Strachan et al. 2019: 24, 42). A small D-shaped annexe containing a series of pits beneath an assumed floor deposit (context 167) was attached to the south-west corner of Building 3. The internal pits contained whetstones and hammerscale suggesting that small-scale ferrous metalworking took place in the annexe (Strachan et al. 2019: 48–50; 114). The walls of Building 3 and its annexe lay directly on top of the natural glacial till (022).

Excavation revealed that the interior of Building 3 was divided into two distinct areas, which had likely been separated by a wattle partition (Strachan et al. 2019: 112). The eastern end was sunken and been cut and infilled with pebbles, cobbles and boulders (157) in a soil matrix (166) to create a feature interpreted as a drain or 'sump' (Table 1; Strachan et al. 2019: 44–45). This end of the building had overlying paving slabs and was interpreted as a space for housing animals (henceforth described as the 'byre'; Figs. 2 and 3).

Fig. 2. Building 3 showing (a) interior from the north-east with the stone-paved byre (157) and soil matrix (166); (b) annexe with sectioned pit in reopened 2015 trench; (c) interior with hearth (left of the photo scales) and the stone-paved byre © PKHT

The western end of the structure appeared to be a living area, which centred around a stone-lined hearth (235) and had a thin deposit (162 – max. 0.07 m thick) of dark silty sand containing charcoal flecks and the occasional piece of burnt bone (Strachan et al. 2019: 44-45). This deposit was believed to be an occupation surface owing to its association with material culture, which included stone tools, iron objects, slag, and a spindle whorl with incised markings. Artefact distribution indicated that the living area may have been the site of 'lighter' activities such as spinning, while more 'industrial' activities took place on the eastern floor and the annexe (Strachan et al. 2019: 84). Floor surfaces across all areas of the structure were almost impossible to identify in the field, owing to their ephemeral nature and an absence of obvious stratigraphy. Identification therefore relied on their association with material culture and features such as the hearth, byre paving and underlying annexe pits.

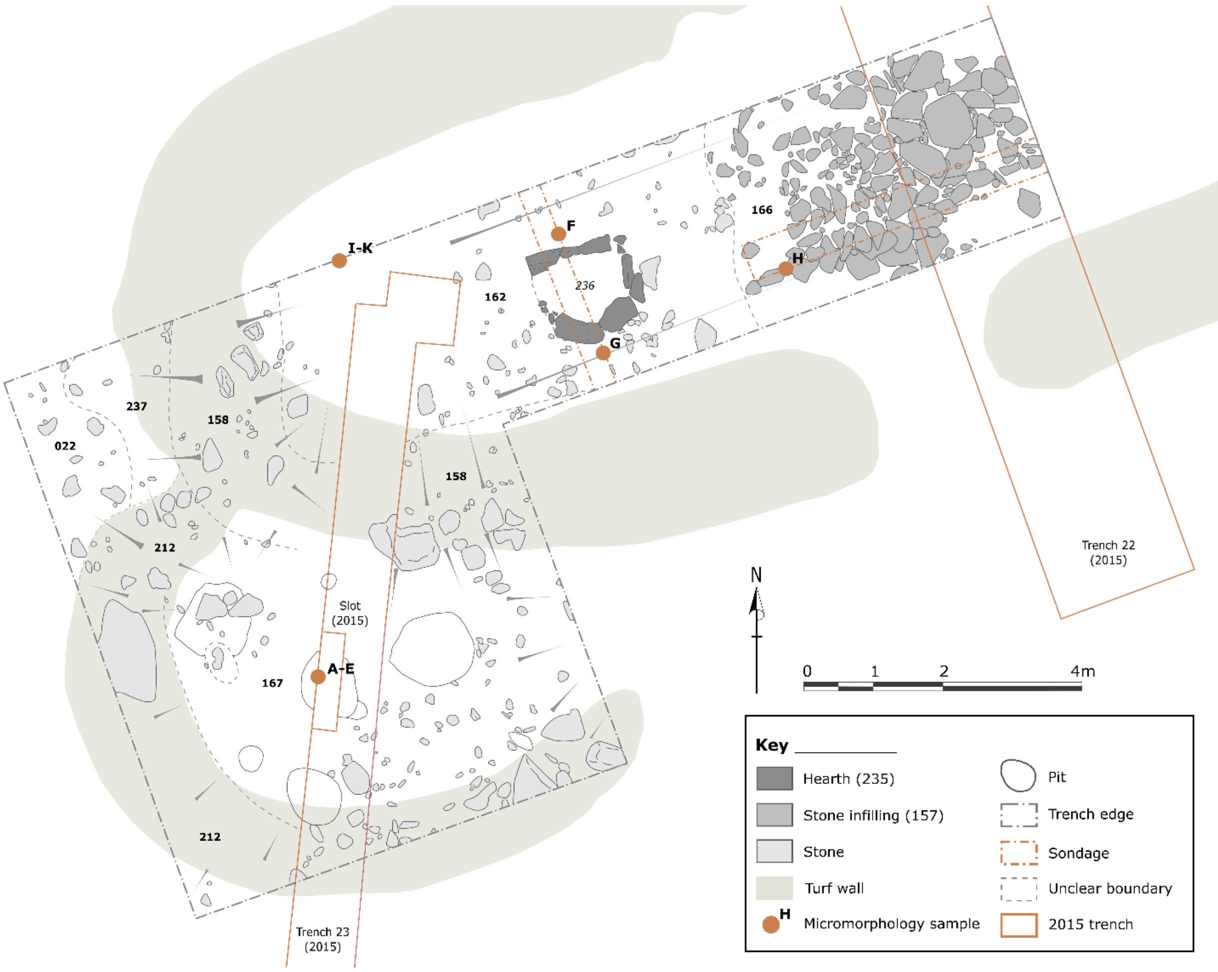

Fig. 3. Mid-excavation plan of Trench 27 (Building 3) showing context numbers, hearth and stone features exposed at the time of sampling in 2016, and location of micromorphology samples (annexe pits superimposed to show location – after Strachan et al. 2016, 2019 © PKHT)

Radiocarbon dating of a cattle bone (*Bos* sp.) from an internal pit, and five samples of roundwood charcoal (*Corylus* sp., *Betula* sp. and *Salix* sp.) indicated that activity associated with Building 3 started in the late 7th or early 8th century AD and continued until the 9th century AD (Strachan et al. 2019: 61-65). Although occasional patches of burnt material were identified, there was no evidence for complete or deliberate destruction by fire, and the building is believed to have been abandoned for other reasons. Building 3 (and other structures within the Lair complex) were excavated as part of the Glenshee Archaeology Project. The results of the excavation and its associated contextual and landscape studies have been published in Strachan et al. 2019.

3. Methods

3.1. Sampling

Samples were collected during the 2016 excavation season from Trench 27, which partially exposed the living and byre areas of the longhouse and the annexe attached to its south-western side (Fig. 3). This trench also captured the westernmost turf wall and extended beyond its exterior edge. Deposits from each area were recorded and sampled using a 0.5 m grid (Table 1). A previous trench excavated in 2015 had been cleaned to the subsoil across the annexe and living area and was excluded from the sampling grid (Fig. 3). Small bulk samples (c. 200ml) for geochemical, microrefuse and magnetic analysis were collected by hand for each grid square and given a unique identifier. Eleven undisturbed block samples for micromorphological analysis were taken from exposed sections using aluminium tins (following Courty et al. 1989 – Supplementary Material 1). Suitable offsite control samples were not identified for this project; the landscape within which the site is situated has been subjected to anthropogenic and animal activity for several thousand years and it was not possible to guarantee true controls. Interpretations have therefore been made with regard to intrasite variability, rather than absolute values.

Table 1. Field description of grid-sampled contexts

Context	Area	Description
162	Living area floor	Firmly compacted dark brown sandy silt loam with very occasional small pebbles, abundant charcoal flecks, occasional fragments of burnt bone and material culture
166	Byre floor	Moderately compacted dark brown sandy silt loam matrix containing moderate amount of small charcoal pieces and occasional fragments of burnt bone
167	Annexe floor	Moderately compacted dark brown silty loam with very occasional small pebbles and occasional charcoal flecks
158	Turf wall (main structure)	Moderately compacted mid brown/orange sandy silt and gravel with occasional sub-angular cobbles and pebbles
212	Turf wall (annexe)	Moderately compacted light brown sandy silt with occasional sub-rounded and sub-angular pebbles
237	Exterior	Dark brown/black silty sand loam containing occasional patches of lighter soil
022	Exterior	Natural glacial subsoil; yellow/brown sandy loam with occasional sub-rounded pebbles and cobbles

3.2. Sediment processing and analysis

Bulk samples were air-dried, gently powdered with a mortar and pestle, and sieved through a 2 mm mesh. The fraction above 2 mm was sorted by hand and examined for microrefuse such as charcoal and burnt bone, and the fraction below 2 mm was used for sedimentary analyses (Rowell 1994). As bulk volumes varied, standardised microrefuse values for a 200 ml sample were calculated. Electrical conductivity (EC) and pH were tested using a Hanna HI98130 meter immersed in 10:20 ml soil:deionised-water suspension. Organic matter content was estimated via loss-on-ignition (LOI) at 550°C. Magnetic susceptibility was tested in 10 ml plastic pots using a Bartington MS2 magnetic susceptibility meter with a low frequency sensor (Dearing 1999).

Element concentration determination was performed by pXRF spectrometry on pressed pellets using a bench-mounted portable X-ray fluorescence analyser (NITON XL3t-Goldd+, Thermo Scientific). Sediment pellets of 10 mm depth were prepared by pressing air-dried and 2 mm sieved bulk samples to a pressure of 11 Tons using a Perkin-Elmer press. The equipment was operated in Cu/Zn mining mode and the instrument was configured to run for 60 seconds per sample. Using proprietary software, elemental concentrations were calculated using a theoretical calibration model (Hf/Ta) from the resultant spectra. Five replicate measurements were taken for each pellet and the mean value was accepted as representative of the grid square. Sixteen elements determined by pXRF consistently returned values within the limit of detection (Al, Ba, Ca, Cr, Fe, K, Mn, P, Rb, S, Si, Sr, Ti, V, Zn and Zr) and were subjected to computational analysis (see 3.3). The complete geochemical dataset, including grid coordinates, is provided in Supplementary Material 2.

Micromorphology thin-sections were prepared following the University of Stirling's (2008) Thin Section Micromorphology Laboratory's standard procedures. All samples were dried using a vapour phase acetone exchange and impregnated with crystic polyester resin under vacuum, before being cut and precision lapped to 30 µm. Slides were scanned using a high-resolution flatbed scanner and initial assessment of the thin-sections was conducted at a 1:1 scale on a lightbox. Microscopic observations were made using Leica M80 and Leica DM2700 P microscopes at a range of magnifications from x4 to x400 with plane-polarised light (PPL), oblique incident light (OIL) and cross-polarised light (XPL). Thin-section description was conducted using the identification and quantification criteria set out by Bullock et al. (1985) and Stoops (2021), with reference to additional texts including Nicosia and Stoops (2017), Macphail and Goldberg (2018), Stoops et al. (2018) and Fitzpatrick (1984).

3.3. Statistics, multivariate data analysis and data presentation

Statistical analyses of all variables (excluding microrefuse) were conducted using IBM SPSS and OriginLab Origin Pro to examine the probability distributions of the data, correlations between different element concentrations, and correlations between element and geochemical results. The dataset consisted of 20 variables (sixteen elements, soil pH, EC, LOI and magnetic susceptibility) for each of the grid squares (n=180). A Shapiro-Wilk test of normality indicated that sixteen of the variables (80%) were not normally distributed. However, as n>30, central limit theorem could be applied, in which normality is assumed when sample sets have a high number of data points (Kwak and Kim 2017). As the variables were measured in different scales, standardisation (z-score) was performed on the variables to ensure that each one contributed equally.

Following initial exploration, the data was subjected to multivariate principal component analysis (PCA) and k-means clustering (k=4) to examine the overall structure of the data and identify whether these correlations were related to different zones within the excavated area (for area membership see Supplementary Material 2). Outliers were included in the data analysis as they were deemed to exhibit variability of the sediments assessed (following Gardner 2018). However, the decision was made to remove grid point P5 from statistical investigation, as it contained maximum or minimum values for eleven of the twenty variables and significantly skewed results. The location of P5 in the turf wall did not provide a sufficient explanation for this variance and it is likely that these results indicate contamination or a highly localised post-depositional process, such as an animal burrow.

PCA results were interpolated by ordinary kriging (using ArcGIS) and compared against distribution maps of the microrefuse and geochemical variables to provide a more visual representation of the data and highlight activity zones within the structure. Graduated symbols in equal intervals were chosen to represent the individual variables, as interpolation of these was not possible between different contexts and across walls. Of the twenty variables subjected to statistical analysis, twelve (pH, EC, organic matter content (LOI), magnetic susceptibility and elements Al, Ba, K, Mn, P, S, Sr and Zn) have been selected for visual presentation here due to their contribution to the interpretation of activity areas and taphonomic processes. Mapping of the additional variables is provided in Supplementary Material 2.

4. Results

4.1. PCA and k-means clustering

Principal component analysis and k-means clustering (k=4) successfully identified correlated variables (Table 2) and related these to differential zones within the longhouse (Fig. 4).

Table 2. Most highly correlated variables (correlation coefficient >0.70)

Variables		Correlation Coefficient
LOI	Al	-0.90
LOI	S	0.88
Mn	Zn	0.83
Al	Ba	0.82
LOI	Ba	-0.81
Al	S	-0.78
Al	K	0.77
LOI	K	-0.77
LOI	Sr	-0.77
Al	Si	0.74
Al	Sr	0.74
K	S	-0.73
Magnetic susceptibility	Mn	0.71

4.1.1. PC1 and C4

The first principal component (PC1) accounted for 38.12% of the total variance (Table 3), and appeared to reflect areas with a higher mineral component and lower organic content, displaying positive loadings for Al, Ba, K, Si and Sr, and negative loadings for LOI, S and EC. This suite of elements is attributed to geological variability (Wilson et al. 2009; Bintliff and Degryse 2022: 2) and broadly corresponded to C4 in the k-means clustering, which strongly identified the annexe and the easternmost end of the living area (Figs. 4 and 5).

Table 3. Results of the first three principal components, showing loadings and % of the variance explained

Components	PC1	PC2	PC3
pH	0.10	-0.58	0.11
EC	-0.34	0.62	-0.14
LOI	-0.94	0.06	0.05
Magnetic susceptibility	0.32	0.74	0.26
Al	0.95	0.05	0.01
Ba	0.87	-0.06	0.23
Ca	0.55	0.26	0.00
Cr	0.17	-0.42	0.47
Fe	0.17	-0.65	0.48
K	0.79	-0.39	-0.22
Mn	0.49	0.56	0.50
P	0.08	0.04	0.60
Rb	0.49	-0.08	-0.12
S	-0.83	0.19	0.19
Si	0.72	0.42	-0.38
Sr	0.81	-0.06	-0.05
Ti	0.66	-0.22	-0.36
V	0.44	-0.32	0.10
Zn	0.70	0.43	0.44
Zr	0.64	0.14	-0.26
% variance	38.12	14.92	9.31
Accumulative %	38.12	53.05	62.35

4.1.2. PC2, C1/C3 and C2

The second principal component (PC2) accounted for 14.92% of the variance and was dominated by positive associations for EC, magnetic susceptibility, Mn and Zn. This corresponded to clusters C1 and C3, which described the majority of the living and byre areas, with C3 strongly correlating magnetic susceptibility, Mn and Zn (Figs. 4 and 5). The enrichment of these elements has been linked to excreta (specifically animal excreta in the case of Mn – see Ottaway and Matthews 1988; Bintliff and Degryse 2022) and appears to preferentially define some of the byre samples. When plotted against the first two PCs, the remaining cluster, C2, linked elevated soil organic matter content (LOI) with S, and the depletion of most elements (Al, Ba, Ca, K, Mn, Rb, Si, Sr, Ti, V, Zn, Zr). This identified the turf walls and samples taken from the exterior of the longhouse.

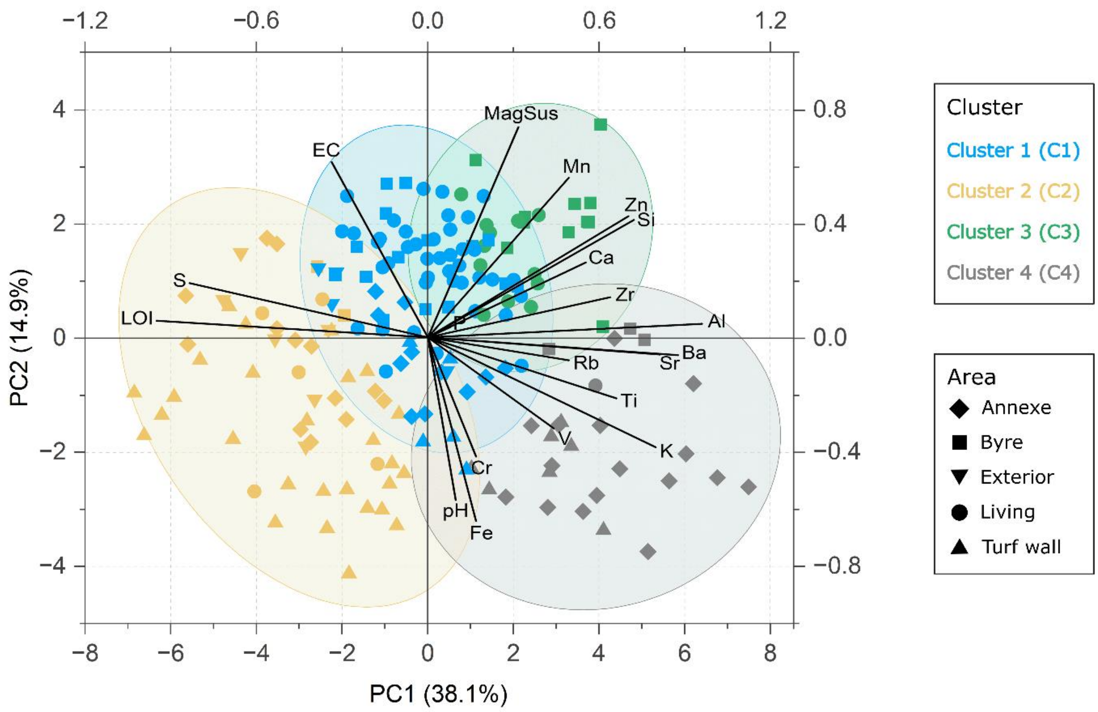

Fig. 4. k-means clustering (k=4) of bulk samples (n=179) against PCA results PC1 and PC2 with 95% confidence ellipses (colours identify cluster membership; symbols denote area membership)

4.1.3. PC3

The third principal component (PC3) accounted for 9.31% of the variance, with positive loadings for Cr, Fe, Mn, P and Zn, and negative loadings for Si and Ti which most likely reflects soils with a reduced mineral component relative to more anthropogenically-associated elements. This related to the living/byre divide, the turf wall of the main structure, and an area within the annexe (Fig. 5). Enrichment of P and Zn is a common indicator of human habitation (Wilson et al. 2009; Bintliff and Degryse 2022), and has been linked to the decomposition, charring and ashing of organic material, such as plant matter or excreta (Davidson et al. 2007; Milek and Roberts 2013). Positive loadings for Fe and Mn may also indicate the presence of redoximorphic features formed in areas that have been periodically waterlogged; these features are also known to fix P in redox-sensitive soils (Vepraskas et al. 2018: 426; Gasparatos et al. 2019). Fe is also commonly associated with the residues of smithing activity (Veldhuijzen 2003). As the first three principal components accounted for 62.35% of the total variance, higher PCs did not appear to reflect clear distinguishable effects and are not discussed further.

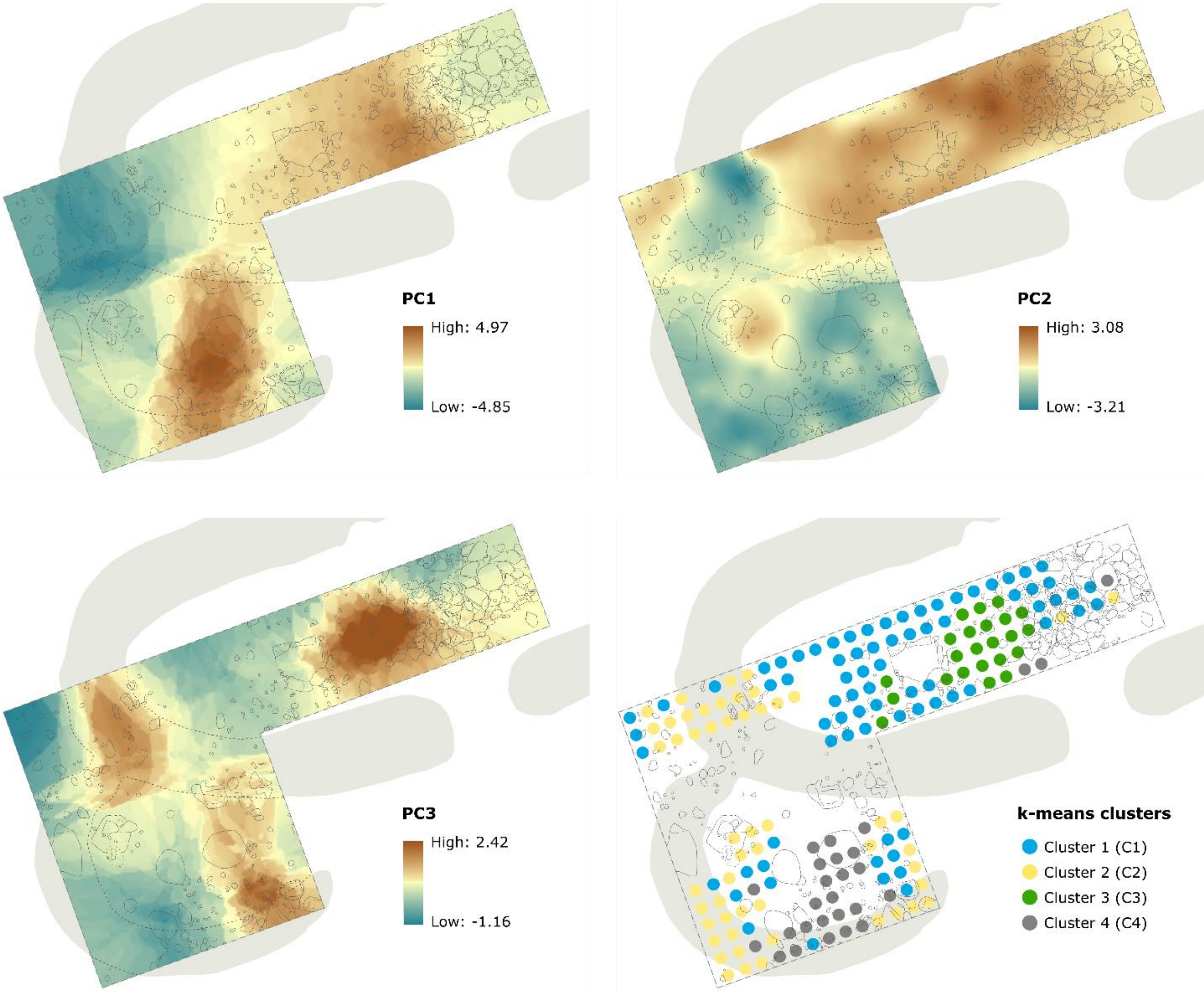

Fig. 5. Interpolation of principal component analysis (PCA) results and distribution of k-means cluster membership

4.2. Distribution mapping

Distribution plots of the point data strongly corroborated the results of the PCA and k-means clustering analysis and provided additional information regarding activity zones and taphonomic processes.

4.2.1. Microrefuse

Charcoal and burnt bone were the only microrefuse types recovered from the bulk samples, reflecting the site's relatively limited artefact record (Fig. 6; see also Figure 4.3 in Strachan et al. 2019). Charcoal was predominately present within the living and byre areas of the longhouse, with a significant concentration occurring along the westernmost part of the byre's central axis (Fig. 6). The comparative lack of charcoal within the annexe, turf wall and exterior areas indicates this is the result of more intense dumping, spreading, and/or trampling of hearth residues in the interior of the structure. The different concentrations between the living and byre areas may also reflecting different maintenance practices within the interior itself. Burnt bone distribution followed a broadly similar pattern to the charcoal, although recovery was extremely low.

4.2.2. pH

Conditions were highly acidic across all contexts (pH 3.2–4.7) and likely accounted for the very limited recovery of bone and organic artefacts (Kibblewhite et al. 2015; Strachan et al. 2019: 78). There was a general trend towards higher pH values in the annexe and across its turf wall, however the tight range for the site suggests that it may be unwise to afford this observation any further interpretation.

4.2.3. Electrical conductivity (EC)

Electrical conductivity was depleted in the easternmost end of the living area and the south-east corner of the but had no clear matches in the elemental plot distributions, other than S. This may be related to sulphate (SO_4^{-2}), however these salts (ions) have a number of sources (e.g. soils, rocks, plants and food), so cannot be used to indicate any one particular material. The correlation between EC and S was also not amongst the most highly correlated variables across the datasets (Table 2). Several element correlations with EC were found to be statistically significant at the 0.01 level (Al, Ba, Cr, Fe, K, S, Sr, Ti and V – Supplementary Material 2).

4.2.4. Organic matter content (LOI)

Organic matter concentrations varied across the site but were notably elevated in parts of the byre (13.8–18.3%), exterior (9.2–22.9%) and turf walls (9.2–27.4%), as well as a small area of the annexe. Enhancement in the turf wall was expected and is almost certainly related to the high organic content of the turf material used in its construction, though was preferentially enhanced in the main longhouse. Within the byre, accumulations of organic matter are likely to have included feed, bedding materials, and animal waste. The elevation within the annexe is more nuanced and is discussed further in 4.2.6.

4.2.5. Magnetic susceptibility

The strong loading of magnetic susceptibility in the living and byre areas identified in PC2 and C3 was clearly presented in the spatial distribution maps, with the highest values recorded at the divide between the living and byre areas. The magnetic enhancement of the living and byre area indicates the presence of soil particles, pebbles and/or iron nodules that were magnetically enhanced by heating (Milek and Roberts 2013: 1853). Heated soil material from the base of the hearth may have become mixed with wood ash residues and subsequently spread across the structure interior (Nesbitt et al. 2013: 14).

4.2.6. Multi-element analysis

Alongside the Mn and Zn enrichment identified in PC2 and C3, the living and byre areas had broad elevations of elements Ba, Ca, P and Sr, with a strong concentration at the living/byre divide (Figs. 7 and 8, see also Supplementary Material 2). This suite of elements are common indicators of human habitation, comprising trace elements and plant macronutrients most often linked to the decomposition or burning of plant matter and excreta (Entwistle et al. 1998; Cook et al. 2005; Davidson et al. 2007; Wilson et al. 2008; Bintliff and Degryse 2022). More specifically, Mn can indicate the presence of animal waste, supporting interpretations for the housing of animals within the structure's interior (Ottaway and Matthews 1988).

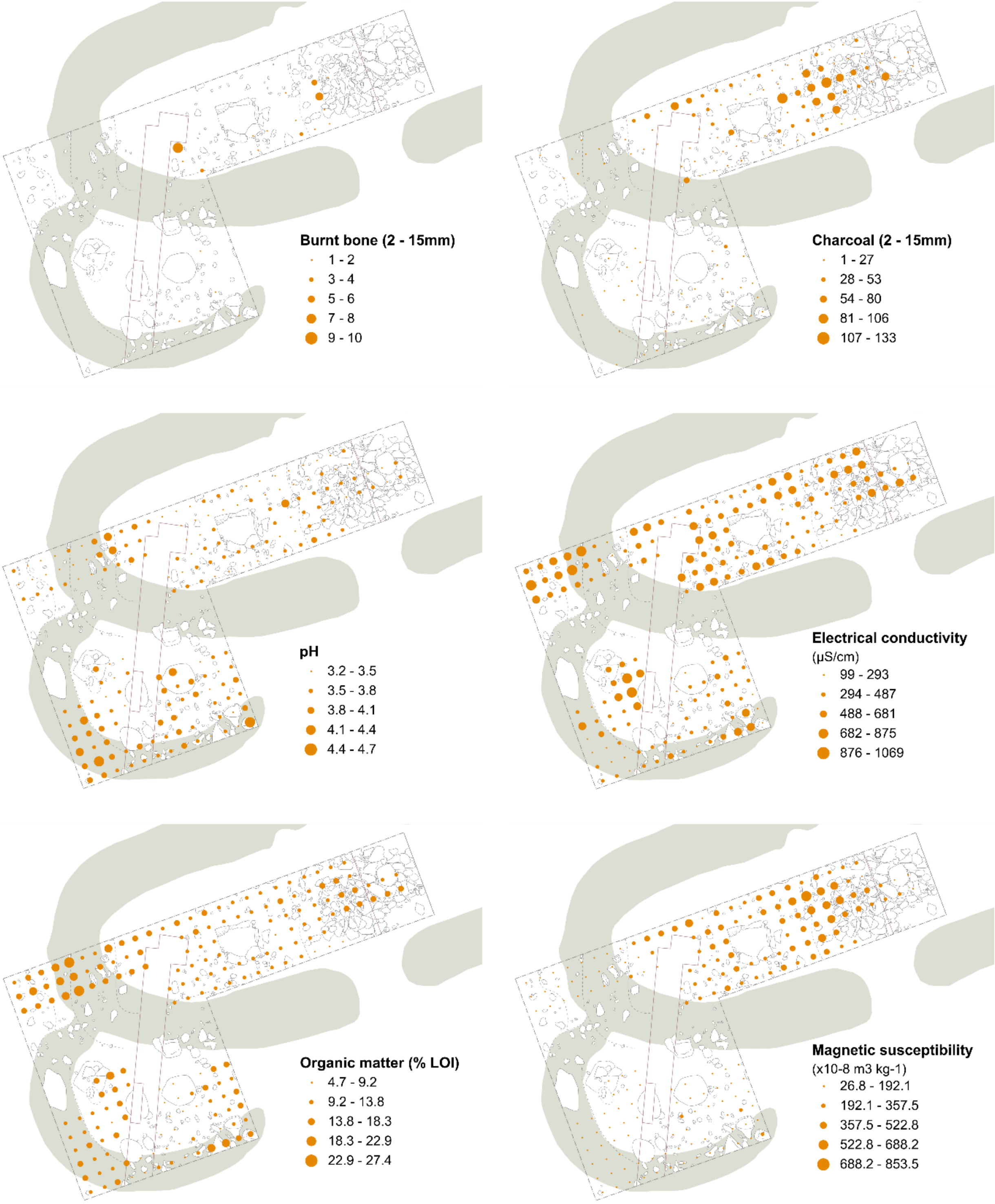

Fig. 6. Distributions of burnt bone, charcoal, pH, electrical conductivity (EC), percent organic matter (loss-on-ignition at 550°C), and magnetic susceptibility

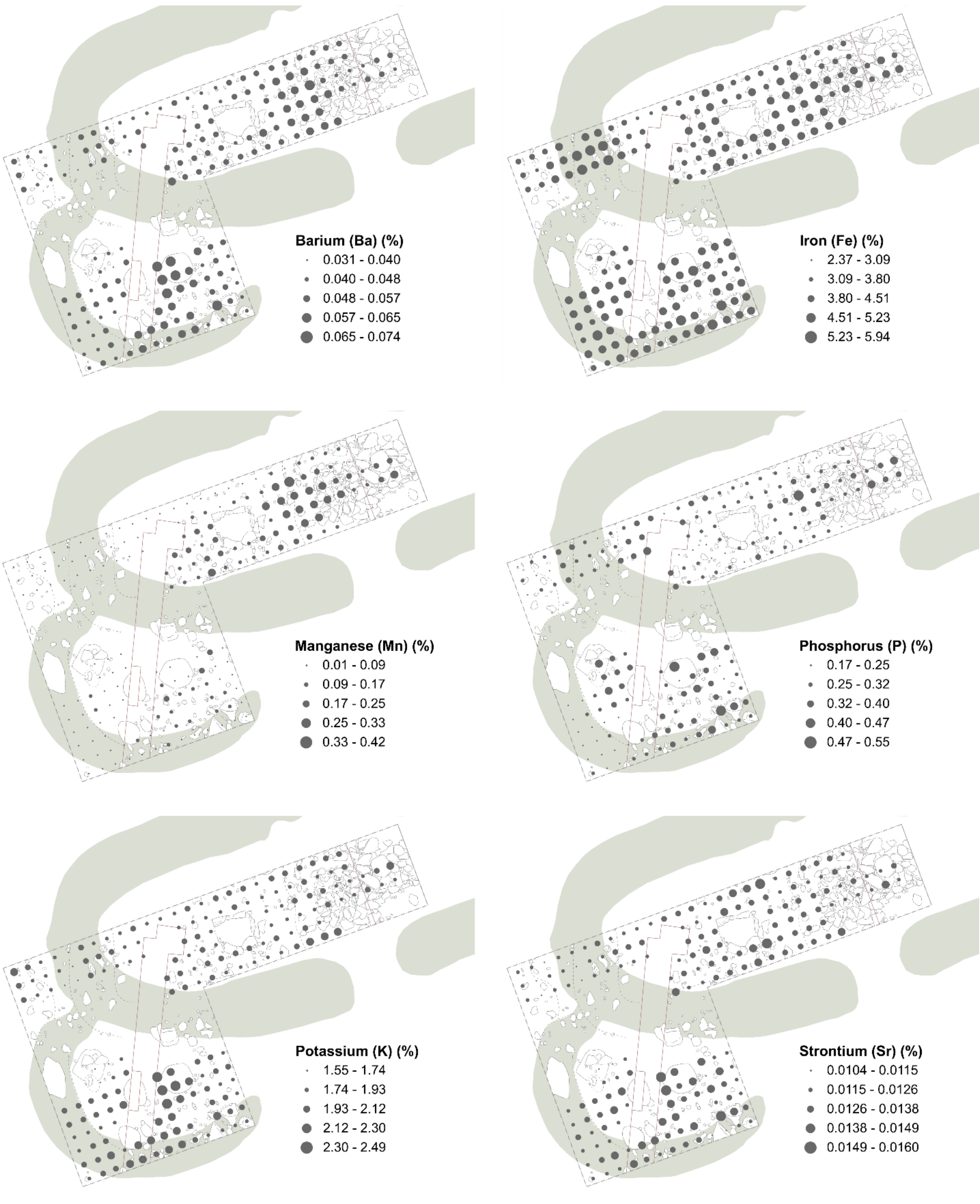

Fig. 7. Distributions of barium (Ba), iron (Fe), manganese (Mn), phosphorus (P), potassium (K) and strontium (Sr)

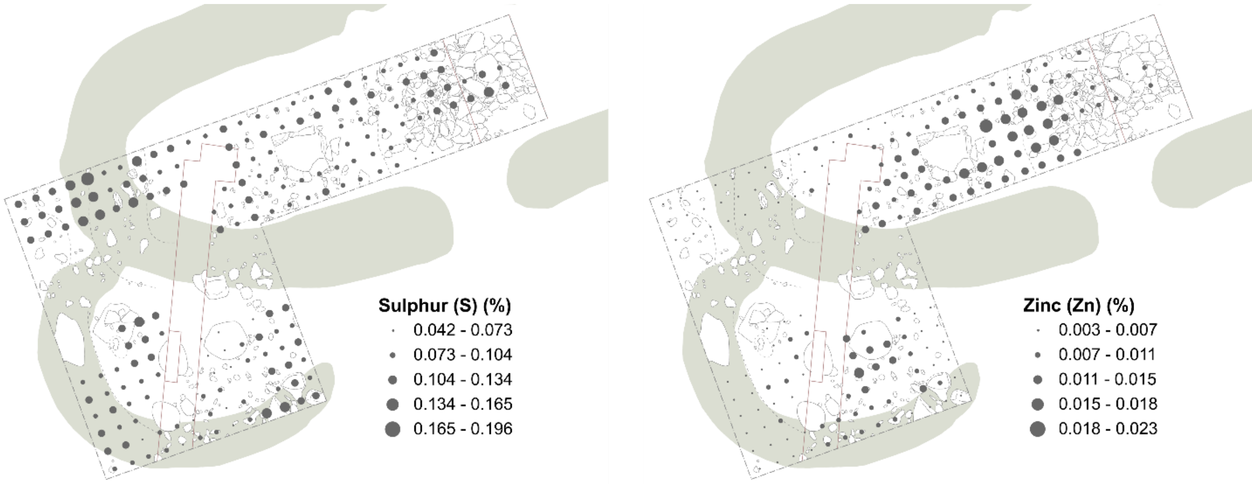

Fig. 8. Distributions of sulphur (S) and zinc (Zn)

Two different patterns of elemental enrichment were observed in the annexe. Levels of P and S were highest towards the northwest corner and corresponded to elevations in both organic matter content (LOI) and EC, whilst towards the east of the annexe there was a marked elevation of Al, Ba, Fe, K, P and Sr, and a very low concentration of organic matter (4.7–9.2%). A series of large pits lay directly beneath the sampled surface and the differential enrichment could be related to the content of the pits (or associated activities) if substantial bioturbation caused some mixing of the sampled surface and the pit fills. This would support observations made during excavation, which identified that the pit in the northwest corner was highly organic and contained an abundance of cattle bones, whilst the easternmost pit was less organic and contained charcoal lenses and hammerscale (Strachan et al. 2019: 49). However, the gap in sampling caused by the 2015 trench does enhance this contrast and the annexe's original elemental signatures may have been more nuanced.

4.3. Micromorphological evidence

4.3.1. Hearth area of the longhouse

The two thin-sections taken either side of the hearth, samples GS16-F and GS16-G, contained layers related to the living area floor (162) and the construction of the hearth (for section drawings see Supplementary Material 1). Context 162 contained 10-20% amorphous, decomposed organic matter (comparative with the values quantified through LOI) and displayed extensive staining by organic acid pigmentation (Table 4; detailed descriptions and interpretations in Supplementary Material 1). As with all thin-sections from the site, phytoliths were not readily identifiable and may have been masked by the organic pigmentation of the fine mineral component. The layer was highly disturbed with intrusive subsoil aggregates (5-10%) and a high degree of bioturbation evidenced by a granular microstructure and large earthworm channels. Areas of better-preserved fabric and distinct aggregates were identified by lower porosity (10-20%), horizontal planar voids and the horizontal orientation of charcoal and minerals (Fig. 9). These areas maintained an internal channel structure and are unlikely to have resulted from compaction during the sampling process. Instead, they appear to represent very limited but tangible evidence of a relic floor within the living area of the longhouse (see Rentzel et al. 2017; Borderie et al. 2020). Given the proximity of the samples to the hearth, the relatively low quantity of charred material (2-5%) in the floor layer is surprising but reflects the results of microrefuse distribution (Fig. 6). This may indicate extensive maintenance practices and even the use of floor coverings within the living area (see 5.2).

4.3.2. Western end of the longhouse

Thin-sections GS16-I, GS16-J and GS16-K were taken from the western end of the interior to investigate an area of unusually clear stratigraphy with alternating orange and dark brown/black lenses (Supplementary Material 1, Fig. 4). The orange lenses were readily identifiable in thin-section and were composed almost entirely of rubified fine mineral material, with a very low organic component (<2%) indicative of Bfe or AB horizons (Table 5). These burnt lenses were situated between layers that were stained dark brown by organic pigmentation, as well as black lenses rich in charred and partially-charred organic matter (40-50%). These charred lenses included a significant wood component (15-30%) primarily from deciduous trees and most likely from the birch or willow family (*Betula*; *Salix/Populus spp.*). Many of the lenses contained evidence of digging – intrusive soil aggregates with a yellowish-brown, dotted fabric similar to the site's natural subsoil (022). Orange lenses 162.3 and 162.5 also contained a significant quantity of iron nodules and intercalations (5-10%), which can develop in periodically waterlogged environments (Fig. 9) (Simpson et al. 1999; Vepraskas et al. 2018). Iron intercalations were not identified in any other thin-sections, suggesting that they may not have developed *in situ* and the soils may have been introduced from wetlands. Although numerically assigned as part of the interior floor (162) during excavation, these lenses did not show any evidence of compaction by trampling and are therefore not interpreted as an accumulation of floor deposits.

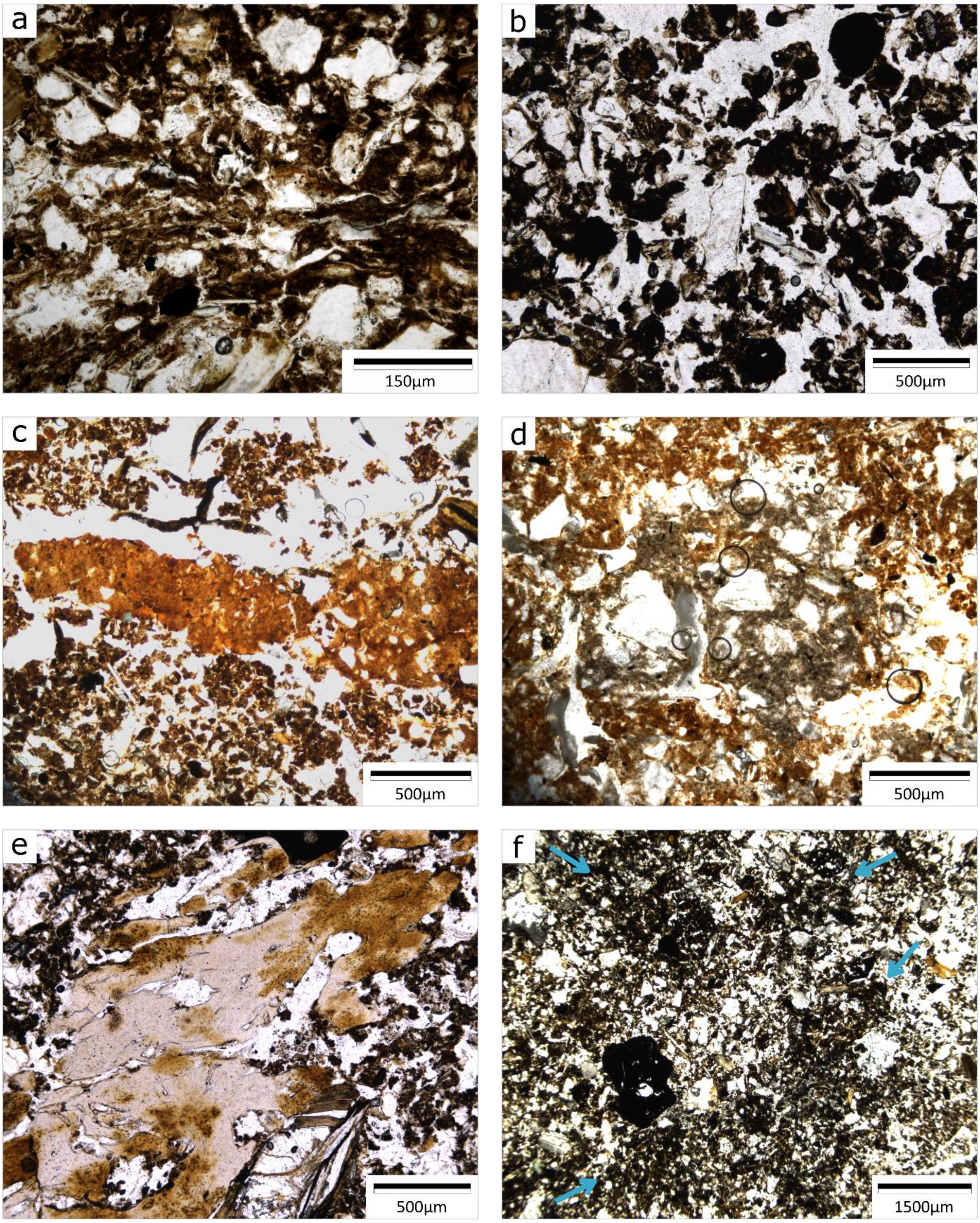

Fig. 9. Photomicrographs (PPL) of (a) GS16-F, context 162, showing relic floor aggregate with horizontal planar voids and horizontal orientation of charcoal and minerals; (b) GS16-F, context 162, showing earthworm channels and granular microstructure as evidence of extensive bioturbation; (c) GS16-I, context 162.1, showing Fe pedofeature (intercalation) in turf stack; (d) GS16-K, context 162.5, showing rubified material and paler, more clay-rich aggregate indicative of digging; (e) GS16-H, context 166, showing pitted bone fragment in surrounding organic-rich sediment; (f) GS16-H, context 166, showing compacted zones (highlighted with blue arrows) of more organic, less porous spongy microstructure in byre area

The exact function of this living area is unclear but the sequence of lenses with markedly different organic matter concentrations could be consistent with the soil profile of cut turfs and may represent a turf stack used to construct an internal furnishing (Huisman and Milek 2017; Romankiewicz et al. 2020; Russell et al. 2021). This may also explain the presence of iron features, as moisture is essential for turf construction and sods may have been favourably sourced from wet environments (Walker 2006: 7–8; Milek 2012; Huisman and Milek 2017: 113; Prado and Noble 2022: 7–8). In this instance, the sequence of thin-sections appears to capture at least three partial turf profiles – a mix of one inverted and two non-inverted turfs. Possible interpretations include an internal turf feature (such as a bench or stool) that burnt *in situ*, or collapse from the turf wall which was associated with a contemporary or later burning episode. The inclusion of such a significant wood component could have resulted from the remains of wooden artefacts or an associated decorative or supportive structure, such as wattle panelling (as found in Scottish vernacular 'creel houses'; Fenton and Walker 1981; Cheape 2014).

4.3.3. Byre area

The layer captured at the byre-end of the structure, context 166 in thin-section GS16-H, was noticeably different to the floor deposits in the living-end of the house. Bioturbation appeared to be less extensive throughout and the layer did not display the granular microstructure of context 162, although it did contain a large number of empty and partially-filled earthworm channels. Compaction and organic matter content gradually increased towards the bottom of the thin-section and localised subangular blocky microstructure was identified in compacted areas at the base of slide. At least five sublinear areas of darker, less porous spongy microstructure were identified across the layer and contained a small number of horizontal and sub-horizontal planar voids (Fig. 9). These horizontal cracks and compacted zones are interpreted as subtle evidence of trampling within this area of the longhouse (Rentzel et al. 2017).

Context 166 contained a similar concentration of amorphous, decomposed organic matter (10-20%) to the floor deposits in the living area of the building but had a noticeably different charred organic component. It was primarily plant-based (2-5%) and included unidentified decomposed plant matter that was subsequently burnt, as well as charred cereal grains, monocot stems and small seeds. Charred wood was more limited (<2%) but included pine (*Pinus spp.*) and diffuse porous charcoal (*cf. Betula/Salix spp.*) from young twigs and a small fragment of two-year-old roundwood hazel (*Corylus sp.*). This was also the only thin-section to contain any bone, which was fragmented and pitted.

Table 4. Summary of descriptive sediment attributes, inclusions and post-depositional alterations (stratigraphic units over multiple slides have been summarised as a single entry)

	Structure			Void Types*			Fine Material			Organic Matter		Inclusions			Pedofeatures		
Slide/unit	Textural class	Microstructure	Course:fine (100µm) ratio	Channels and vughs	Planar	Compound packing voids	Nature of fine material (PPL)	Colour of fine material (OIL)	Birefringence fabric (XPL)	Charred	Uncharred	Bone	Intrusive aggregates	Rubified fine material	Fe/Mn nodules	Fe intercalations	Excremental
A 167	Organic silt loam	Spongy with channels and crumb	20:80	▪▪▪▪▪▪▪▪		▪▪▪▪▪▪▪	Dark brown; dotted	Dark brown	Stipple-speckled; localised undifferentiated	▪	▪▪▪▪		▪▪				▪▪▪▪
A/B/C 220.1	Sandy silt loam	Spongy and crumb with localised channels	30:70	▪▪▪▪▪▪▪▪▪		▪▪▪▪▪▪	Mid-brown; dotted	Yellowish-brown	Stipple-speckled	▪	▪▪▪		▪▪				▪▪▪▪
D 220.2	Organic sandy silt loam	Granular and spongy	25:75	▪▪▪▪▪▪▪▪		▪▪▪▪▪▪▪	Dark brown; mid-brown; dotted	Dark brown; yellowish-brown	Stipple-speckled; localised undifferentiated	▪▪▪▪	▪▪▪▪		▪				▪▪▪▪▪
D/E 201	Silt loam	Spongy with localised channels	15:85	▪▪▪▪▪▪▪▪▪▪		▪▪▪▪	Yellowish-brown; dotted	Yellow	Mosaic-speckled	▪▪	▪▪		▪▪				▪▪▪
F 162	Organic sandy silt loam	Granular with channels and localised subangular blocky	55:45	▪▪▪▪▪▪▪▪	▪	▪▪▪▪▪▪	Dark brown; dotted	Dark brown	Stipple-speckled; localised undifferentiated	▪▪	▪▪▪▪		▪▪▪	+	+		▪▪▪▪▪
F 283a	Sandy silt loam	Granular with channels and localised spongy	60:40	▪▪▪▪▪▪▪	+	▪▪▪▪▪▪▪▪	Dark brown; yellowish-brown; dotted	Dark brown; brownish-yellow	Stipple-speckled	▪▪	▪▪▪		▪▪▪▪		▪		▪▪▪▪
G 283b	Sandy silt loam	Granular; spongy and channels	55:45	▪▪▪▪▪▪▪▪▪	+	▪▪▪▪▪▪	Brown; yellowish-brown; dotted	Brown; brownish-yellow	Stippled-speckled	▪▪	▪▪▪		▪▪▪		▪		▪▪▪
F 284	Sandy loam	Spongy with channels and localised crumb	50:50	▪▪▪▪▪▪▪▪▪▪		▪▪▪▪	Yellowish-brown; speckled	Yellow	Stipple-speckled	▪	▪				+		▪▪
G 284**	Sandy loam	Crumb/granular with spongy and channels	50:50	▪▪▪▪▪▪▪▪▪▪	+	▪▪▪▪▪	Yellowish-brown; brown; dotted	Brownish-yellow	Stippled-speckled	▪▪	▪▪		n/a**		+		▪▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* void frequency refers to % total void space (following Bullock et al. 1985; Stoops 2021: 73)
** see Supplementary Material 1, Table 7.2

Table 5. Summary of descriptive sediment attributes, inclusions and post-depositional alterations (stratigraphic units over multiple slides have been summarised as a single entry)

	Structure			Void Type*			Fine Material			Organic Matter		Inclusions			Pedofeatures		
Slide/context	Textural class	Microstructure	Course:fine (100µm) ratio	Channels and vughs	Planar	Compound packing voids	Nature of fine material (PPL)	Colour of fine material (OIL)	Birefringence fabric (XPL)	Charred	Uncharred	Bone	Intrusive aggregates	Rubified fine material	Fe/Mn nodules	Fe intercalations	Excremental
H 166	Organic sandy silt loam	Spongy with crumb and localised subangular blocky	20:80	▪▪▪▪▪▪▪▪▪▪	▪▪	▪▪▪▪	Brown; dark brown; dotted	Yellowish-brown; brown	Stipple-speckled	▪▪▪	▪▪▪▪	▪	▪	+	+		▪▪
I 162.1	Very organic sandy silt loam	Granular	25:75	▪▪▪▪▪▪		▪▪▪▪▪▪▪▪▪	Dark brown; orangish-brown; dotted	Dark brown; orangish-brown	Stipple-speckled; localised undifferentiated	▪	▪▪▪▪▪		▪▪	▪	▪▪	▪▪	▪▪▪▪▪▪
I/J 162.2	Organic sandy silt loam	Spongy with localised crumb and channels	30:70	▪▪▪▪▪▪▪▪▪▪		▪▪▪▪▪	Mid-brown; dotted	Yellowish-brown	Stipple-speckled	▪▪▪▪	▪▪▪▪		▪▪▪	▪▪	+		▪▪▪▪
J 162.3	Sandy silt loam	Spongy with localised crumb and channels	20:80	▪▪▪▪▪▪▪▪▪▪		▪▪▪▪	Orange; orangish-brown; speckled	Orange; yellowish-brown	Stipple-speckled	▪	▪▪			▪▪▪▪▪▪▪▪	▪		▪▪
J 162.4	Organic matter	Spongy and granular with channels	60:40	▪▪▪▪▪▪▪▪▪▪		▪▪▪▪	Black; orangish-brown; dotted	Black; orange to yellowish-brown	Undifferentiated; localised stipple-speckled	▪▪▪▪▪▪▪	▪▪		▪▪	▪▪	+		▪▪▪▪
K 162.5	Sandy silt loam	Spongy with localised crumb and channels	20:80	▪▪▪▪▪▪▪▪▪▪		▪▪▪▪▪	Orange; orangish-brown; speckled	Orange; yellowish-brown	Stipple-speckled	▪	▪		▪▪	▪▪▪▪▪▪	+	▪	▪▪▪▪
K 162.6	Sandy silt loam	Spongy with localised crumb	30:70	▪▪▪▪▪▪▪▪▪▪		▪▪▪	Mid-brown; dotted	Yellowish-brown	Mosaic-speckled	▪▪▪	▪▪▪			▪	▪		▪▪▪
K 162.7	Organic matter	Spongy with granular and localised channels	20:80	▪▪▪▪▪▪▪▪▪▪		▪▪▪▪	Black; dark brown; dotted	Black; orangish-yellow	Undifferentiated; localised mosaic-speckled	▪▪▪▪▪▪▪	▪▪▪		▪	+	+		▪▪▪▪▪
K 162.8	Sandy silt loam	Crumb and spongy with localised channels	35:65	▪▪▪▪▪▪▪▪▪▪		▪▪▪▪▪	Yellowish-brown; dark brown; dotted	Orangish-yellow; yellowish-brown	Stipple-speckled	▪▪▪	▪▪▪		▪▪		+		▪▪▪▪
K 022	Sandy loam	Spongy with localised channels	55:45	▪▪▪▪▪▪▪▪▪▪		▪▪	Yellowish-brown; dotted	Orangish-yellow	Stipple-speckled	▪	▪				+		▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* void frequency refers to % total void space (following Bullock et al. 1985; Stoops 2021: 73)

4.3.4. Annexe

Thin-section series GS16-A to GS16-E was taken from a section through the central annexe pit to investigate the nature of the overlying floor (167) and the composition of the pit fill. The floor layer contained 10-20% amorphous, decomposed organic matter (comparative to the values in both the living and byre areas) and occasional intrusive aggregates of lighter, less-organic material with a higher clay component (Table 4). These aggregates displayed similar characteristics to both the primary fill (201) and the natural subsoil and may have resulted from digging and/or bioturbation.

In general, the pit fills were relatively sterile and provided little evidence for the function of the pits or the activities within the annexe. Neither fill appeared to represent domestic or hearth waste. They were very poorly sorted and lacked inclusions other than low concentrations of charcoal and amorphous charred material (<5%). Primary fill (201) had a very limited concentration of amorphous, decomposed organic matter (2-5%) and a similar concentration of charred wood that included pine (*Pinus spp.*) and diffuse porous charcoal (*cf. Betula/Salix spp.*). Of note were several intrusive aggregates of compacted greyish-yellow clay (2-5% porosity) that displayed a unistriated b-fabric. These aggregates had lenses of horizontally-orientated minerals but did not contain any horizontal voids which may have indicated that they originated from a floor or trampled surface. The secondary fill (220.1) was more organic, with 5-10% amorphous, decomposed organic matter and brown staining from organic acid pigmentation, but a more limited charred component (<2%). The fabric is suggestive of an A or amended A horizon that had lost some of its granular structure and may represent a surface soil or upturned turf that was used to seal the primary fill. Lens 220.2 was identified by a notable elevation of both charred organic matter (10-20%) and amorphous, decomposed organic matter content (10-20%) that likely represents the decomposed O-A interface of an upturned turf. Burning does not appear to have occurred *in situ* but the notable charred component of lens 220.2 suggests that the turf would have been sourced from an area close to anthropogenic activity.

5. Discussion

5.1. Preservation and post-depositional processes

The integrated geoarchaeological results indicate that high soil acidity, coupled with bioturbation and free-draining siliceous soils, resulted in the dissolution of wood ash residues and decomposition of almost all organic material, including bone. This is a common feature of mainland Scottish archaeology and has frequently been linked to the relative dearth of material recovered from early medieval settlement sites (Reid and Milek 2021). Site stratigraphy has similarly suffered in these conditions, with soil turnover and channels, primarily from earthworms and modern roots, having impacted all sampled areas. There was almost no evidence of relic occupation surfaces in the field or in thin-section, and although excavation indicated that Building 3 had at least two phases of use, this was not reflected in the micromorphological analysis. However, fragments of surviving microstructure were identified in all archaeological layers indicating that they had not been completely destroyed by post-depositional processes.

5.2. Identification of ephemeral occupation surfaces

During the excavation and sampling process for this study, there was concern over whether the floor surfaces in the living area, byre and annexe had been accurately identified. Due to their thin and seemingly fragmented nature, their recognition in the field was tentative and largely relied on an association with internal features and material culture. Given that very little evidence of relic occupation surfaces was retained in thin-section, micromorphology was unable to clarify this issue and provided little indication of differentiated activity zones. However, the geochemical evidence demonstrated that these floor surfaces could be readily identified by the chemical and magnetic signatures of the three different activity areas sampled. This provides an interesting contrast to studies that determined micromorphology to be the most powerful geoarchaeological tool for interpretating site activity (Milek and Roberts 2013). Whilst this may be the case in well-preserved contexts, the spatial geochemical evidence presented above has proved far more successful in differentiating activity areas at a site where preservation is poor and occupation surfaces are ephemeral.

5.3. Interpretations of household activities and the use of space

Geoarchaeological and multivariate analysis supported the interpretation that Building 3 had three distinct activity areas – a living area centred around a hearth, a stone-paved 'byre' area for housing animals, and an annexe that functioned as a workshop (Fig. 10). *In situ* burning was observed at various parts of the structure during excavation but was not ubiquitous across the interior and does not appear to represent an abandonment event.

The living and byre areas were characterised by enhanced magnetic mineral signatures, charcoal, burnt bone, and chemical elevations associated with organic matter and waste. Since there was no evidence of extensive burning, the magnetic enhancement likely reflects the presence of soil particles and charcoal taken from a domestic hearth and deliberately spread across these areas or trampled into the surface over time. Peat and turf are unlikely fuel sources, as their characteristic reddened deposits and charred plant material were not present in the field or in thin-section (excluding the *in situ* burnt turf feature present in thin-sections GS16-I to K). Wood ash, mixed with heated soil from the base of the hearth, is therefore a more likely source.

The spreading of ash is known from 10th-century Iceland (Milek and Roberts 2013), post-medieval Scottish blackhouses and crofts (Nesbitt et al. 2013; Smith 1996) and 19th/20th-century ethnography and ethnoarchaeology (Fenton 1978; Milek 2012), where the floors of turf houses and animal buildings were treated to absorb moisture and odours. At the site of Þverá in Iceland, ash was frequently spread on house floors and subsequently removed when floor layers became too thick (Milek 2012: 134). Ash is also a natural insecticide and would have provided the additional benefit of protecting wooden posts and furnishings from fungal decay (Hakbijl 2002). The spreading of hearth waste throughout both the living area and the byre at Lair may therefore be interpreted as evidence of floor maintenance practices.

Elevated signatures relating to organic matter and its ash were most highly concentrated between the living and byre areas, supporting the interpretation that a panel divided the interior of the structure (Strachan et al. 2019: 112) (Fig. 10). Debris could have accumulated against the partition through actions such as sweeping, trampling or kicking and scuffing, or organic matter from animal feed, bedding or waste may have preferentially piled up against the divide and subsequently degraded. The charred young twigs and two-year-old roundwood hazel identified in the byre thin-section may be related to this accumulation of material or, alternatively, represent fragments of a wattle divide that burned *in situ*. Additional sources include hearth tinder from spread ash, and any combination of these inputs are likely to have resulted in a concentration of charcoal and organic plant remains within this area of the house. The elevation of manganese along the byre's central axis also supports interpretations that the sunken area functioned as a drain or 'sump', removing excreta out of the house and away from the living area (Strachan et al. 2019: 61). The compaction observed in the byre end could therefore indicate that its sunken nature was enhanced through poaching by livestock trampling when animals were stalled over winter (Strachan et al. 2019: 128).

Fig. 10. Interpretive plan of Lair Building 3, based on integrated field, artefact, microrefuse, geochemical and micromorphological evidence. For interpretation of the colour in this figure and legend, the reader is referred to the web version of this article.

Although bioturbation was extensive, it did not always provide a sufficient explanation for the thin and ephemeral occupation surfaces observed in the living area of the structure. Floor coverings have been explored as a reason for the lack of stratigraphy at other early medieval sites (Taylor 1990: 27; Driscoll 1997; McGill 2004), and there is certainly evidence for their use in Scotland either side of the early medieval period. Remains from the Biggings and Underhoull Viking longhouse in Shetland have pointed towards the use of wooden floors that would have supported hearths and kept the floor dry (Crawford and Ballin Smith 1999; Bond 2013; Sharples 2020: 14–16), whilst bracken has been identified as a flooring material used in Iron Age Perthshire (Miller 1997) and southwest Scotland (Cavers et al. 2011; Crone et al. 2018; Robertson 2018; Robertson and Roy 2021). Large quantities of bracken were also found at Dundurn hillfort in Perthshire, perhaps having been gathered for use as thatch, bedding or flooring (Alcock 2003: 111). Bracken would have been readily available at Lair and a favourable choice as it decomposes slowly and acts as a natural insecticide (Donnelly et al. 2002; Strachan et al. 2019: 122). However, the low values of organic matter content and plant macronutrients within the living area may counteract this hypothesis, or at least suggest the removal and/or use of different floor coverings between the living and byre areas. Given that there was no surviving evidence for floor coverings in any of the thin-sections, it is likely that any materials degraded or were removed prior to site abandonment. It is similarly possible that microstratigraphy resulting from cumulative ash or floor layers could have been removed by frequent maintenance (as in Þverá – see Milek 2012: 134), and visual evidence of these residues lost to decomposition, bioturbation, and other soil processes.

The living area would have contained sitting and sleeping spaces, most probably located along the northern and western turf walls (Fig. 10). As this area was only partially excavated and sampled, the geochemical evidence is limited, however the probable turf sequence identified in thin-section may indicate that such furnishings were constructed from stacked turves – a common feature of later vernacular architecture (Walker 2006: 32). Evidence for the method of turf construction at Lair was very limited due to natural degradation and bioturbation of the soils. However, the turf lenses captured in thin-section and identified elsewhere on the site appeared relatively thin, even accounting for the effects of degradation and compaction (Strachan et al. 2019: 120). This suggests that thinner turves (*divet* or *divot* in Scots) rather than thick blocks (*faill*, *fale* or *feal* in Scots) were the preferred method of construction (Strachan et al. 2019: 120). The results of PC3 also indicate that different turf was used in the construction of the main house and the annexe, with the former being richer in organic matter and iron (Fig. 10). This may be evidence for phasing, where the difference in turf quality and saturation resulted from different locations, seasonality, or a change in environmental conditions over time. However, if the two structures are contemporary, this could suggest that the wetter (and thus better) turves were preferentially used for the construction of the main house, reflecting relative value and function.

The annexe was most clearly differentiated from the main structure by a very low magnetic enhancement, suggesting that it was not treated with ash as in the living and byre areas and had not been the location of heat-based activities. The different elemental signatures within the annexe itself may be related to the content of the pit fills and suggests that separate activities took place within certain zones. The northwest corner appeared to be involved in the disposal and/or processing of organic material (including cattle bones), whilst the eastern part may have related to the maintenance of tools (Fig. 10). This is most acutely demonstrated on the PC1 map (Fig. 5) which also correlates this signature to the easternmost end of the living area, perhaps representing the 'industrial' blade maintenance activities reflected in the stone artefact record (Strahan et al. 2019: 84). Interestingly, deposits of hammerscale identified in the easternmost pit were not reflected in the magnetic susceptibility results from the overlying occupation surface, suggesting that the actual smithing of iron tools occurred elsewhere. Of course, the use of the annexe and these areas may have changed over time and not all of the pits are likely to have been in use simultaneously. Thin-sections from the central pit confirmed that its primary fill was sealed by turf or surface soil, suggesting the burial of waste material, but did not provide additional evidence for its source.

5.4. Evaluation of an integrated geoarchaeological approach

The results presented in this study have supported the use of multi-method, integrated geoarchaeological approaches in studying activity areas on poorly preserved archaeological sites. On its own, charcoal distribution was able to identify the main activity space and floor maintenance practices, however bone needed to be interpreted in the context of the site's preservation conditions. High soil acidity provided a clear explanation as to why only calcined bone was recovered and why organic artefacts and unburnt bone were completely absent in the > 2 mm bulk sediment fraction. Overlapping the charcoal and burnt bone datasets with magnetic susceptibility then indicated that they most likely represented the remains of hearth residues. Although variation in the pH level was limited at Lair, changes in soil pH and soluble salt concentrations (which affect metal survival) can occur at the microscale and any artefact and microrefuse distributions should always be interpreted in relation to these factors (Milek and Roberts 2013).

Overlaying the PCA of variables with k-means clustering results showed the components which caused the most distinction between areas and helped interpret their contributing inputs – for example, strong loadings of Mn and Zn (and to some degree P) in the byre samples (C3) provided key support for the interpretation of its function as an animal house. This approach also supported (and was supported by) micromorphological evidence of iron features in the turf-stack, which complemented evidence for Fe enrichment in PC3 and C2 that corresponded to samples taken from the main structure's turf wall. Furthermore, the decision to examine the data through both statistical analysis and spatial mapping allowed the relationships and areas identified through *k*-means to be visualised and understood in relation to the excavated site and its distinct activity zones. In addition, it permitted the identification of more refined areas (such as the divide between the living and byre areas, and the differential turf wall and annexe signatures) which were not clearly represented by the statistical analyses alone.

On its own, micromorphology was able to provide clear evidence for the post-depositional processes affecting the site and provide insight as to its limited stratigraphy. Moreover, it was able to identify fragments of surviving microstructure and filter out the effects of bioturbation – a feat not achievable in the field or through chemical survey. To date, very little micromorphological work has been conducted on early medieval upland sites, and this study has helped to address outstanding questions regarding floor preservation and the extent of bioturbation on occupation deposits (Reid and Milek 2021: 746). However, micromorphology was not able to add great detail to the identification of activity areas and it is therefore very promising that geochemical and multi-element analysis has the potential to recognise differential activity zones, even when floor layers are not well preserved or clearly visible in the field or in thin-section. This demonstrates the value in conducting geoarchaeological investigation but also the need for integrated approaches, rather than a reliance on individual techniques. Given the success of PCA and k-means clustering in differentiating living areas from turf walls and non-domestic areas, integrated approaches that involve statistical investigation may be particularly useful in scenarios where upstanding structural evidence such as walls, banks and hearths are absent or fragmented.

6. Conclusion

The ephemeral occupation surfaces found within Pictish houses have long restricted efforts to characterise domestic life in the home. By combining field observations with geochemical analyses, micromorphology and statistical investigation, it was possible to corroborate findings, support hypotheses, and recover new detail about site use and preservation. The integrated methods conducted in this study have therefore demonstrated the role geoarchaeology can play in elucidating aspects of daily life and living conditions and provided the clearest insights to date. Their analysis proved successful in identifying activity areas and relating this to maintenance practices, the organisation of space, and post-depositional processes. Most significantly, the integrated approach has shown that soils can indeed have surviving characteristics of the use of space, even if floors are not preserved well enough to be clearly defined in the field or in thin-section.

This study has presented the results from an early medieval settlement structure in Scotland but offers a methodology that can be applied to archaeological sites around the world. Given the depth of information recovered from a poorly preserved site, it is likely to offer an even greater wealth of detail in well-preserved contexts. In scenarios where floors are thin, fragmentary or not readily apparent during excavation, an integrated geoarchaeological approach could help to identify occupation deposits, differentiate activity zones, clarify domestic and non-domestic areas, recognise human and animal living spaces, and identify the sources of inputs. This has immense potential to illuminate settlement records in geographic blackholes, where floors and occupation surfaces are routinely elusive and ephemeral.

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Author Contributions

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Competing Interests

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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7. Research Paper 4

The role of geoarchaeology in the interpretation of fragmented buildings and occupation surfaces: The case of coastal settlements in northeast Scotland

Vanessa Reid, Karen Milek, Charlotte O'Brien, Óskar G. Sveinbjarnarson and Gordon Noble
(submitted to Geoarchaeology)

Despite the success of geoarchaeological methods in elucidating activity areas and site formation processes (as demonstrated in Chapter 6), archaeologists are often reluctant to apply them if they suspect preservation is poor or stratigraphy is not visible in the field. To assess the role that geoarchaeology can play in the interpretation of fragmented structures, this second case study provides an assessment of site formation processes in sites whose structural elements and occupation deposits have been truncated (RQ *i*, *iii*, *v and vii*; Chapter 1, section 1.3). This contrasts with the structure at Lair (Chapter 6), whose ground plan was upstanding, clearly visible, and confined the known occupation surfaces. The paper applies the same suite of geoarchaeological methods as Chapter 6 to investigate two buildings of unknown function in the early medieval coastal promontory forts of Burghead (Moray) and Dunnicaer (Aberdeenshire). This research has been submitted to the journal *Geoarchaeology* and is currently awaiting review.

The concept and methodology of this paper were developed in partnership with co-author Karen Milek (primary supervisor to this thesis). As the first author of this paper, I was responsible for the sampling at Dunnicaer, and the laboratory analyses, data collection, statistical analyses, visualisation, and the interpretation of all results. I wrote the first full draft of the paper and corrected subsequent drafts based on comments by the co-authors. Charlotte O'Brien conducted the charcoal identifications presented in the micromorphological analysis; Gordon Noble was the director of both sites, and Óskar Sveinbjarnarson collected the on-site samples at Burghead and provided the archive material and supporting documents which aided site analysis. All authors read and agreed to this version of the manuscript prior to submission.

The role of geoarchaeology in the interpretation of fragmented buildings and occupation surfaces: The case of coastal settlements in northeast Scotland

Vanessa Reid[a*], Karen Milek[a], Charlotte O'Brien[a], Óskar G. Sveinbjarnarson[b] and Gordon Noble[c]

Abstract

Around the world, poorly preserved buildings and occupation surfaces often represent the primary evidence for archaeological structures and settlements. Integrated geoarchaeological methods, such as soil chemistry and micromorphology, can be used to maximise the information obtainable from such deposits regarding site preservation and the use of space. However, archaeologists are often reluctant to apply these methods if they suspect preservation is poor or stratigraphy is not visible in the field. To assess the role that geoarchaeology can play in the interpretation of fragmented structures, this paper presents the results of two case studies in which multiple geoarchaeological methods were applied to poorly preserved occupation surfaces and fragmented buildings in early medieval coastal settlements in northeast Scotland. Micromorphology was fundamental in recognising floor layers, maintenance practices, and post-depositional processes that affected stratigraphic visibility at the macroscale. When subjected to principal component analysis (PCA), the geochemical data were not only able to provide new detail about activity areas, but also successfully identify and filter out the effects of modern contamination. Most significantly, the integrated approach demonstrates that fragmented buildings and occupation surfaces retain surviving characteristics of the use of space, even if floors are not preserved well enough to be clearly defined in the field or in thin-section.

Keywords

Geoarchaeology, micromorphology, settlement, site formation processes, preservation

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1. Introduction

Settlement remains are a vital resource for understanding the organisation and structure of past societies (e.g. Parker Pearson and Richards, 1994; LaMotta and Schiffer, 1999). Geoarchaeological investigation has proven to be a particularly effective tool in characterising past human activity on settlement sites and providing detail on the rituals that governed everyday life (Jones et al., 2010; Milek & Roberts, 2013; French, 2015). However, archaeologists are often reluctant to apply these methods if they suspect preservation is poor or stratigraphy is not visible in the field (Goldberg, 1988, 2008; Macphail et al., 2003; Cannell 2012, p. 11; Goldberg &Aldeias, 2018). The reasons for this vary. In some instances, it appears to be a lack of awareness of the capabilities of geoarchaeological techniques, whilst in others the decision to omit geoarchaeological analysis follows a cost-benefit assessment (Goldberg, 2008; Goldberg & Aldeias, 2018). Underlying of all these, however, is the assumption that little detail can be retrieved from truncated structures and occupation deposits. Further driving this perspective is the fact that the vast majority of geoarchaeological case studies are conducted on well-preserved sites with surviving structural elements and clear stratigraphic sequences (e.g. Boivin, 2000; Milek & Roberts, 2013; Borderie et al., 2020), and there is comparatively little research on how integrated methods can be used to improve understanding in cases where sites are poorly preserved and highly fragmented.

Equating thin, homogenous, fragmentary, or truncated deposits with a paucity of evidence for settlement activity belies several fundamental principles of archaeological site formation. First, certain depositional events may not be apparent to the naked eye, and their identification requires microscopic examination (Goldberg & Macphail, 2006; Karkanas & Goldberg, 2016; Macphail & Goldberg, 2018). Second, there are multiple taphonomic factors that can modify the appearance of stratigraphy and affect the integrity of its (micro)structure and associated artefact and ecofact assemblages – though do not necessarily result in the complete eradication of the original structure and composition (Huisman, 2009; Kibblewhite et al., 2015; Kooistra & Pulleman, 2018). Third, many residues of human activity are minute and only identifiable at a microscopic or molecular scale (Weiner, 2010; Shackley, 2011). Omitting their analysis is therefore likely to miss key evidence of settlement character and create less detailed and less reliable interpretations of archaeological structures and their assemblages.

There are numerous geoarchaeological techniques that can be used to study the residues left behind by humans and animals. Soil micromorphology has long proven itself to be the gold standard in resolving microstratigraphic detail and understanding the composition and preservation of archaeological deposits (Courty et al., 1989; Banerjea et al., 2015; Robertson & Roy, 2021). Geochemical assessments – such as pH, organic matter content and multi-element analysis – can provide corroborating evidence of burial conditions and aid the interpretation of activity areas (Smith, 1996; Entwistle et al., 1998, 2000; Milek & Roberts, 2013; Nielsen & Kristiansen, 2014; Borderie et al., 2020). These techniques have been shown to be particularly effective when integrated into multi-method datasets (Jones et al., 2010; Mentzer & Quade, 2013; Milek & Roberts, 2013; Shillito, 2017; Kidder et al., 2021; Reidsma et al., 2021).

In order to assess the effectiveness of geoarchaeological methods in elucidating formation processes and the use of space in fragmented buildings, this study focuses on sites where poor preservation has limited interpretations of archaeological settlement remains. Poorly preserved buildings and occupation surfaces are a common feature of early medieval settlement in Scotland, where secure traces of structural elements and internal deposits are often absent, heavily fragmented, or poorly defined (Dunwell & Ralston, 2008, p. 133–140; Driscoll, 2011; Reid, 2021; Reid & Milek 2021). Ephemeral building traditions and the use of non-earthfast materials appear to be contributing factors, and features are commonly truncated through later agriculture, urban development, coastal erosion, or stone robbing (Dunwell & Ralston, 2008, p. 140; Noble et al., 2020, p. 320; Reid & Milek, 2021). The lack of structural remains is typically accompanied by a poor volume of finds and has been exacerbated by a tendency towards small scales of excavation. Very little geoarchaeological investigation has been conducted in the region and the paucity of evidence has resulted in several cases where clarifying site function, status, or date has proved almost impossible (e.g. Ralston, 1987).

Excavations conducted by the University of Aberdeen's 'Northern Picts' project provided an opportunity to apply integrated geoarchaeological methods to two poorly preserved buildings on the Scottish coast (Fig. 1). Investigations at Burghead and Dunnicaer coastal promontory forts established the potential survival of fragmented floor layers within partial structures, whose architectural elements had been truncated, degraded, or lost to erosion. Dedicated geoarchaeological sampling strategies were employed during the 2016 excavation season to investigate the integrity of these floor deposits and whether they retained any micro-evidence of site activity. The distributions of microrefuse and geochemical properties – pH, soluble salt content (electrical conductivity), organic matter (loss-on-ignition), magnetic susceptibility and multiple elements – were subjected to principal component analysis (PCA), mapped across the excavated surfaces, and compared against the results of micromorphological analysis to assess the role geoarchaeology could play in interpreting fragmented buildings and occupation surfaces.

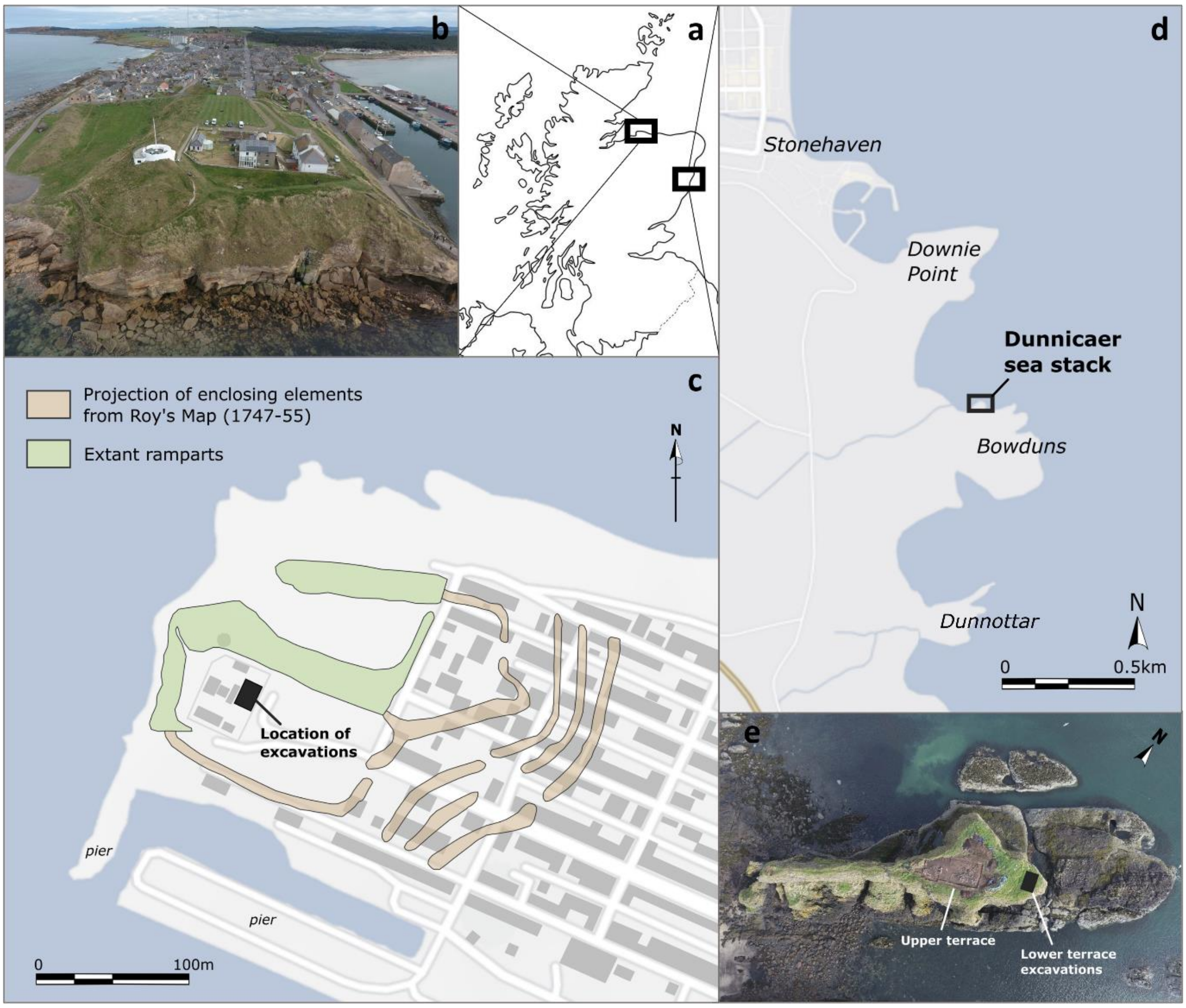

Fig. 1. Composite image of Burghead (left) and Dunnicaer (right) study sites showing (a) location of study sites in relation to Scotland; (b) oblique aerial image of Burghead looking south-east with 2017 excavation trenches; (c) location of 2015-17 Burghead excavation trenches in relation to Burghead town and Pictish ramparts; (d) location of Dunnicaer sea stack on Aberdeenshire coast; (e) aerial drone image of Dunnicaer sea stack during 2017 excavations, showing extensive erosion at north-east end and location of lower terrace excavations (photographs © Gordon Noble; diagram (c) adapted from Noble et al. 2018; contains OS Data © Crown copyright and database right 2022; © University of Aberdeen)

2. Study Area

2.1. Burghead

Situated on a peninsula that projects northwest into the Moray Firth, Burghead fort (NRHE No. 16146; NJ 1090 6914) is one of the largest and most impressive Pictish settlements currently known (Foster, 2014, p. 46; Noble, 2019, p. 46) (Fig. 1). Situated in an area of sandstone outcrops, with overlying marine deposits of gravel, sand and silt, the fort covered an area of around 5.5 hectares, with stone ramparts defining an upper and lower citadel (Alcock, 2003, p. 192–197; Foster, 2014, p. 47; BGS, 2022). Evidence suggests that the fort was occupied since at least the 6th century AD and was destroyed by fire in the 9th or 10th century (Noble & Evans, 2022, p. 111). Much of the fort was lost during the construction of a planned village and harbour at the beginnings of the 19th century, which revealed a deep well and up to 30 Class I symbol stones carved with bull imagery (Oram, 2007). These monuments, and the immense size and complexity of the fort, all indicate that Burghead was a major Pictish power centre during the first millennium AD.

Excavations by the Department of Archaeology, University of Aberdeen, have been ongoing since 2015 and are adding considerable detail to an existing corpus of work on the site (MacDonald, 1862; Young, 1891, 1893; Small, 1969; Edwards & Ralston, 1978; Ralston, 2006). They have so far identified evidence of structures in both the upper and lower citadels, revealed complex timber-laced ramparts, and recovered a wealth of artefacts including coins, iron weaponry, and carved bone pins. Parts of the site have already been undermined by coastal erosion and recent seasons have been conducted as part of a Historic Environment Scotland funded excavation programme intended to capture as much information as possible before it is lost to the sea.

The 2015–17 excavation seasons explored the extent and nature of Building 2 – a sub-rectangular structure in the upper citadel, which measured at least 8 m in length and 5 m in width (Figs. 2 and 3). A highly fragmented turf and stone wall survived only in the northwest end and measured up to 0.3 m in height, 0.7 m in width and 4 m in length (Fig. 2, a). This part of the structure contained a heavily robbed hearth made of flat flagstones and a thin deposit (context 17040 – max. 0.1 m thick) of fine, dark grey sand interpreted as a floor layer (Fig. 3). A charcoal rich deposit (17039) containing burnt oak timbers overlay this occupation surface at the northwest end and was interpreted as the remains of a timber superstructure which may have been destroyed by fire. Finds included an iron buckle, an iron sword hilt, a 9th century pierced Anglo-Saxon coin and a broken rotary quern.

Fig. 2. Drone images of Building 2 showing (a) final excavation of 2017 trench with hearth (17053) and turf/stone wall; (b) mid-excavation of 2016 trench with (105/106) floor and 2015 baulk (photographs © Óskar G. Sveinbjarnarson)

Preservation became increasingly poor towards the southeast end of the structure, where the turf wall no longer survived. Two deposits – a black, compact sand (105) and an underlying sand containing charcoal (106) – were interpreted as floor layers, with 106 a possible extension of context 17040 (Fig. 2, b, and Fig. 3). Their extent became unclear towards the southeast end of the trench, where 19th century ceramics, postholes, a stone wall, and industrial waste consisting of coal, clinker, cinder and slag were discovered. This indicated that 19th century activity extended down into the early medieval layers and had likely truncated or contaminated archaeological deposits in the southern edges of the trench. Radiocarbon dating of the lower floor (106) placed activity in the 9th–10th century AD however no date was retrieved for 105. A concentration of postholes in the east of the 2016 trench were radiocarbon dated to the 7th–8th centuries AD and a shallow ring-ditch underlay the lower floor of Building 2, providing possible evidence of an earlier structure.

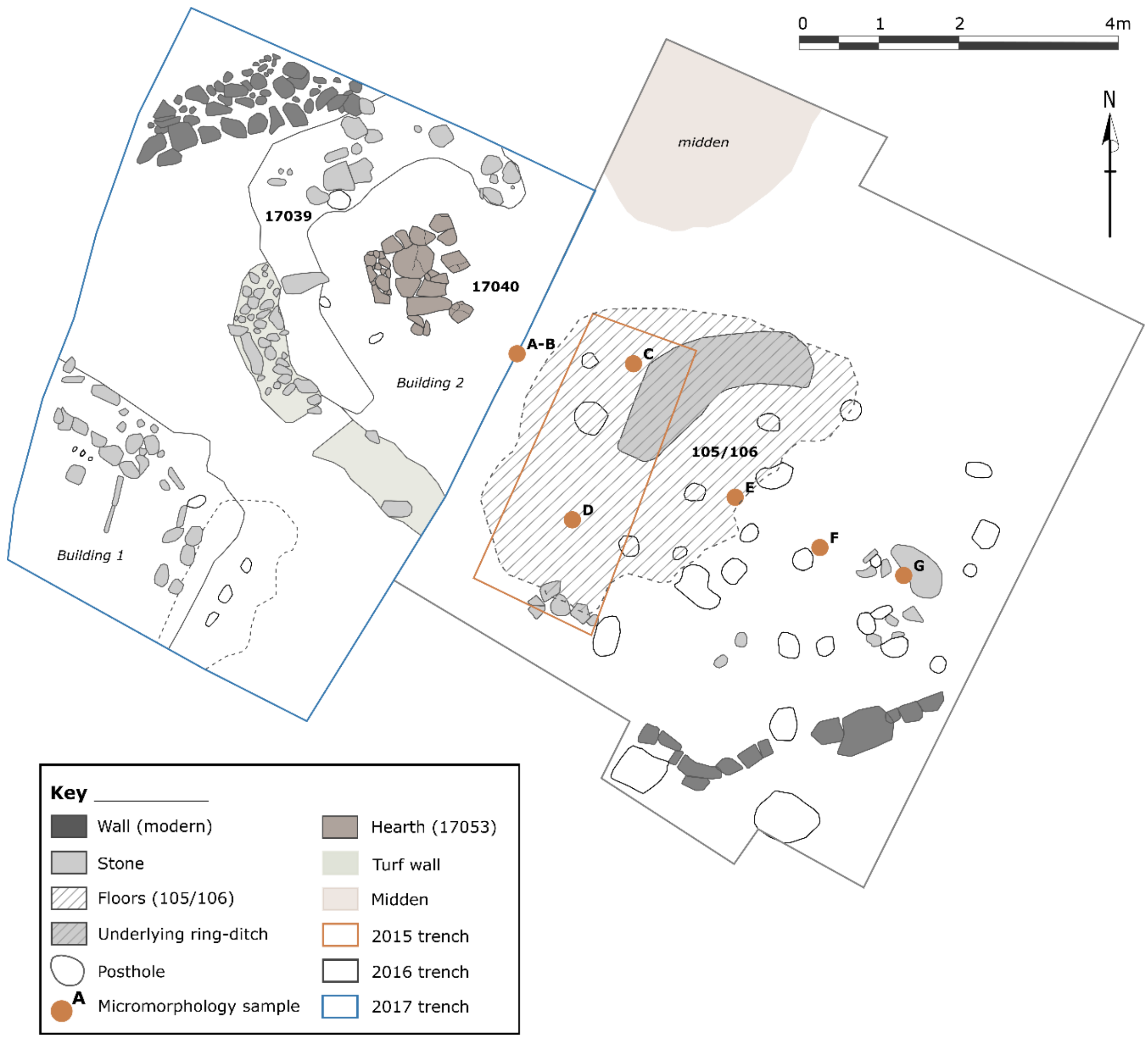

Fig. 3. Final excavation plan of Building 2 showing deposit context numbers, hearth and location of micromorphology samples

2.2. Dunnicaer

Dunnicaer (NRHE No. 37001; NO 8821 8464) is a severely eroded sea stack on the Aberdeenshire coast, just south of the town of Stonehaven (Fig. 1). The stack is composed of conglomerate rock with sandstone veins and stands to a height of 21 m. It measures 54 m long and up to 20 m wide, with the top divided into an upper terrace (max. 24 x 14 m) and a smaller lower terrace (max. 8 x 8 m) (Noble et al., 2020, p. 265). Five Pictish symbol stones were recovered from the stack during the 19th century, and excavation by the University of Aberdeen (2015–17) revealed the remains of a highly eroded promontory fort dated to the Roman Iron Age (1st–4th centuries AD). Evidence included the remains of a timber-laced or framed rampart, multiple structures and hearths, imported Roman Samian and coarse-ware, and burnishing stones for metalworking. Results of the excavation, specialist reports and contextual analysis were published in Noble et al., (2020).

Part of the 2016 excavation focused on exposing deposits and settlement features in the lower terrace. Occupation evidence consisted of two overlying sub-rectangular stone hearths and up to 0.3 m of compacted floor deposits (1009). The stones of the lower hearth (1012) were significantly more fire-cracked than those that made up the upper hearth (1008), indicating intensive and perhaps long-lived use of this feature. To the west of the upper hearth, a distinct charcoal-rich deposit (1007) was interpreted as probable ash rake-out (Fig. 4 and 5). There were no obvious postholes or outer walling associated with the hearths, implying the main structural elements had been lost to erosion or lay outwith the limits of the trench (Noble et al., 2020, p. 319). Preservation was more favourable in the lower terrace owing to a lack of 19th century stone quarrying and cultivation that had truncated features in the upper terrace. Slumped deposits from the upper terrace had also aided the survival of archaeological stratigraphy in the lower terrace. There was no evidence for destruction by fire, and the structure and fort are believed to have been abandoned around the beginning of the 5th century AD (Noble et al., 2020, p. 330).

Fig. 4. Oblique view of the lower terrace trench looking north-east, showing floor (1009), charcoal spread (1007) and upper hearth (1008) immediately prior to bulk sampling (photograph © Gordon Noble)

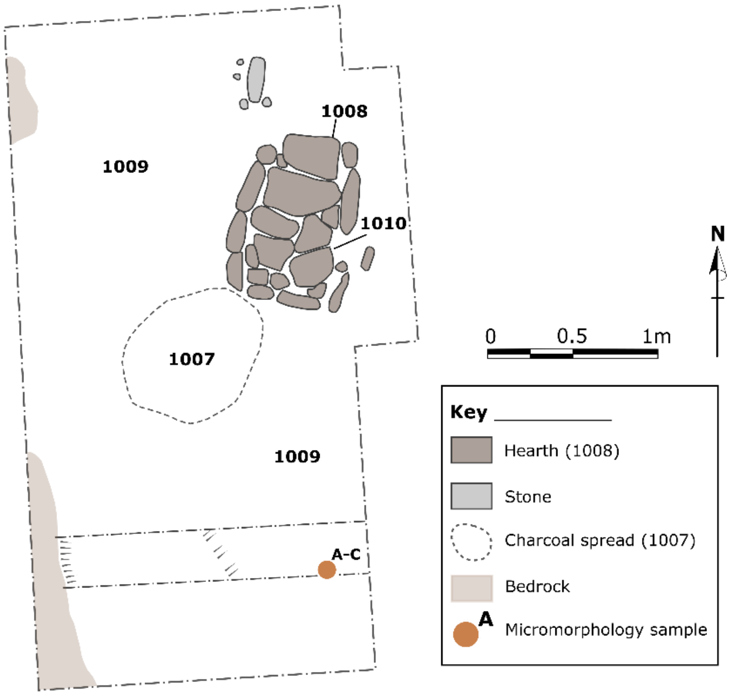

Fig. 5. Mid-excavation plan of the lower terrace trench showing location of micromorphology samples, context numbers, upper hearth and charcoal spread exposed at the time of sampling

3. Methods

3.1. Sampling

Occupation deposits at both sites were recorded and sampled using a 0.5 m grid during the 2016 excavation season. Small bulk samples (c. 200 ml) for geochemical, microrefuse and magnetic analysis were collected by hand for each grid square and given a unique identifier. At Burghead, bulk sampling concentrated on the two overlying surfaces believed to be floor layers to assess their nature and extent, and map post-depositional contamination (Fig. 3). The upper sampled area (n=96) included layer 105, and the lower sampled area (n=131) included layer 106. At Dunnicaer, bulk sampling concentrated on characterising activity surrounding the upper hearth. This occurred on a smaller scale (n=24) owing to the limited space available in the lower terrace (Fig. 5). Given the extent of urban development at Burghead, and Dunnicaer's location amidst agricultural land, it was not possible to source suitable control samples for background levels. Interpretations have therefore been made with regard to intrasite variability.

Undisturbed block samples for micromorphological analysis were taken from exposed sections using aluminium tins (following Courty et al., 1989). The block sampling strategies focused on the interpretation of known/visible occupation surfaces, and at Burghead also involved collecting samples outwith their visible limits in order to clarify the spatial extent of the deposits (block locations and section drawings are provided in Supplementary Material 1).

3.2. Sediment processing and analysis

Bulk samples were air-dried, gently powdered with a mortar and pestle, and sieved with 2 mm mesh. The fraction above 2 mm was sorted by hand and examined for microrefuse such as charcoal and burnt bone, and the fraction below 2 mm was used for sedimentary analyses (Rowell, 1994). As bulk volumes varied, standardised microrefuse values for a 200 ml sample were calculated. Electrical conductivity (EC) and pH were tested using a Hanna HI98130 meter immersed in 10:20 ml soil:deionised-water suspension. Organic matter content was estimated via loss-on-ignition (LOI) at 550°C. Magnetic susceptibility was tested in 10 ml plastic pots using a Bartington MS3 magnetic susceptibility meter with an MS2B dual frequency sensor set on the low frequency setting (Dearing, 1999).

Element concentration determination was performed by pXRF spectrometry on pressed pellets using a bench-mounted portable X-ray fluorescence analyser (NITON XL3t-Goldd+, Thermo Scientific). Sediment pellets of 10 mm depth were prepared by pressing air-dried and 2 mm sieved bulk samples to a pressure of 11 Tons using a Perkin-Elmer press. The equipment was operated in Cu/Zn mining mode and the instrument was configured to run for 60 seconds per sample. Using proprietary software, elemental concentrations were calculated using a theoretical calibration model (Hf/Ta) from the resultant spectra. Five replicate measurements were taken for each pellet and the mean value was accepted as representative of the grid square. Elements which returned values within the limits of detection were subjected to computational analysis (see 3.3). As missing data can affect the validity of statistical analysis, grid squares with element concentrations below the limit of detection (< LOD), were substituted with LOD/2 in accordance with Farnham et al., (2002). Elements whose < LOD values exceeded 25% of the replicates were excluded from statistical investigation (Farnham et al., 2002). The remaining suite of elements comprised Al, Ba, Ca, Cr, Fe, K, P, Rb, S, Si, Sr, Ti and Zr. Complete geochemical datasets, including grid coordinates, are provided in Supplementary Materials 2-4.

Micromorphology thin-sections were prepared following the University of Stirling's (2008) Thin Section Micromorphology Laboratory's standard procedures. All samples were dried using a vapour phase acetone exchange and impregnated with resin under vacuum, before being cut and precision lapped to 30 µm. Slides were scanned using a high-resolution flatbed scanner and initial assessment of the thin-sections was conducted at a 1:1 scale on a lightbox. Microscopic observations were made using Leica M80 and Leica DM2700 P microscopes at a range of magnifications from x4 to x400 with plane-polarised light (PPL), oblique incident light (OIL) and cross-polarised light (XPL). Thin-section description was conducted using the identification and quantification criteria set out by Bullock et al., (1985) and Stoops, (2021), with reference to additional texts including Nicosia & Stoops, (2017), Stoops et al., (2018) and Fitzpatrick, (1984).

3.3. Statistics, multivariate data analysis and data presentation

Statistical analyses of all variables (excluding microrefuse) were conducted using IBM SPSS and OriginLab Origin Pro to examine the distributions of the data, correlations between different element concentrations, and correlations between element and geochemical results. Shapiro-Wilk tests of normality indicated that multiple variables within the Burghead datasets were not normally distributed. However, as both had n>30, central limit theorem could be applied, in which normality is assumed when sample sets have a high number of data points (Kwak & Kim, 2017). As the variables were measured in different scales, standardisation (z-score) was performed prior to multivariate analysis to ensure that each one contributed equally. Outliers were included in the data analysis as they were deemed to exhibit variability of the sediments assessed (following Gardner, 2018).

Principal component analysis (PCA) was performed to examine the overall structure of the datasets, and the results interpolated by ordinary kriging (using ArcGIS) to provide a more visual representation of the data. Interpolated surfaces were compared against distribution maps of the microartefact and geochemical datasets to corroborate results and inform interpretations. Where applicable, distribution maps of additional elements (Cl, Cu, Ni, Pb, V, Zn) excluded from statistical analysis were also generated. Graduated symbols in equal intervals were chosen to represent the individual variables, as interpolation of these was not possible between different contexts and across walls. Burghead's upper surface was represented by graduated symbols in natural breaks (Jenks) as contamination in part of the trench had elevated elemental values to such an extent that more nuanced signatures in archaeological deposits were masked by equal interval mapping. The Dunnicaer sample size of 24 was too small for reliable PCA (see Shaukat et al., 2016), so data was interrogated by the visual comparison of these maps and the results of Spearman's rank correlation coefficient (r_s) for non-parametric data. For each of the sites, selected variables have been chosen for visual presentation due to their contribution to the interpretation of activity areas and taphonomic processes. Mapping of the additional variables is provided in Supplementary Materials 2-4.

4. Results

4.1. Burghead upper surface (containing 105)

4.1.1. PCA results

PCA analysis of the geochemical results from Burghead's upper surface revealed three principal components (PCs) that met the Kaiser criterion (Kaiser, 1960, 1970) and accounted for 79.79% of the total variance (Table 1).

Table 1. Results of the first three principal components for Burghead upper surface, showing loadings and % of the variance explained

Components	PC1	PC2	PC3
pH	-0.39	0.73	-0.41
EC	0.81	-0.25	0.31
LOI	0.96	0.07	-0.04
Magnetic susceptibility	0.88	0.06	0.09
Al	0.92	0.13	-0.12
Ba	0.55	-0.03	0.30
Ca	0.92	0.09	0.07
Cr	0.88	0.14	-0.04
Fe	0.96	0.11	-0.12
K	-0.81	0.12	0.46
P	0.79	-0.03	0.25
Rb	-0.26	0.72	0.58
S	0.87	0.07	-0.02
Si	-0.94	-0.12	0.03
Sr	0.81	0.11	-0.13
Ti	0.93	0.11	-0.11
Zr	0.77	-0.12	0.18
% variance	66.21	7.29	6.29
Accumulative %	66.21	73.50	79.79

The first principal component (PC1) accounted for 66.21% of the total variance and appeared to reflect areas with a higher organic content and lower mineral component, demonstrating high positive loadings (>0.75) for twelve of the seventeen variables (EC, LOI, magnetic susceptibility, Al, Ca, Cr, Fe, P, S, Sr, Ti, Zr) and high negative loadings (>-0.80) for Si and K (Fig. 6).

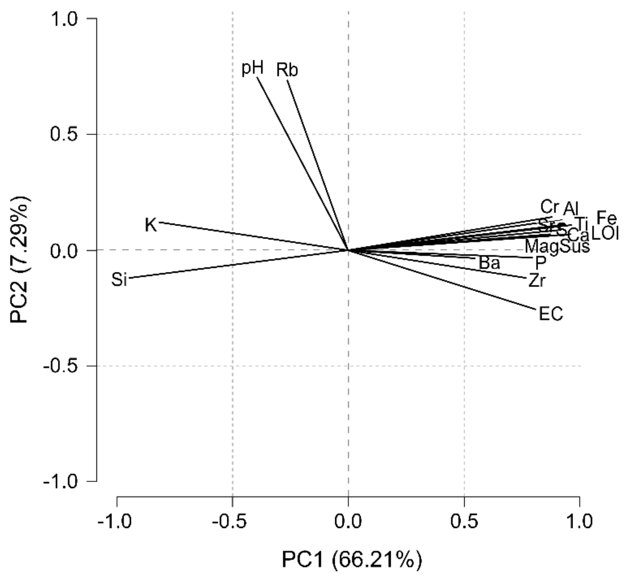

Fig. 6. Results of the first two principal components (upper surface)

PC2 accounted for 7.29% of the total variance and demonstrated high loadings (>0.71) for pH and Rb. PC3 accounted for 6.29% of the total variance and presented moderate positive loadings (>0.45) for Rb and K. These elements are known to be strongly correlated in soils and both PC2 and PC3 are likely to reflect lithogenic signatures (Croffie et al., 2022, p. 819). Across all three PCs, EC displayed a negative correlation with pH indicating that areas with a higher concentration of soluble salts or nutrients were generally more acidic.

4.1.2. Spatial distributions

Spatial plotting of the individual upper surface variables and interpolation of the PCA results permitted an evaluation of how the PCA variance related to patterning and inputs. PC1 primarily related to an area of anthropogenic contamination at the southern edge of the trench (Fig. 7). Here, concentrations of Al, Ca, Sr and Ti were between four and seven times higher than the grid average, with Fe returning concentrations up to eight times higher, and S up to ten times higher (Fig. 8). Distribution maps of the elements excluded from statistical analysis showed that this area was also enriched in Cl, Cu, Ni, Pb, V and Zn, and correlated with high concentrations of modern industrial waste (Fig. 8 – see also Supplementary Material 2). The contaminated area had a high organic content (LOI), suggesting that the elemental enrichment related in part to plant matter and/or human and animal waste, with the area most likely functioning as a 19th century dump or midden (Bintliff & Degryse, 2022).

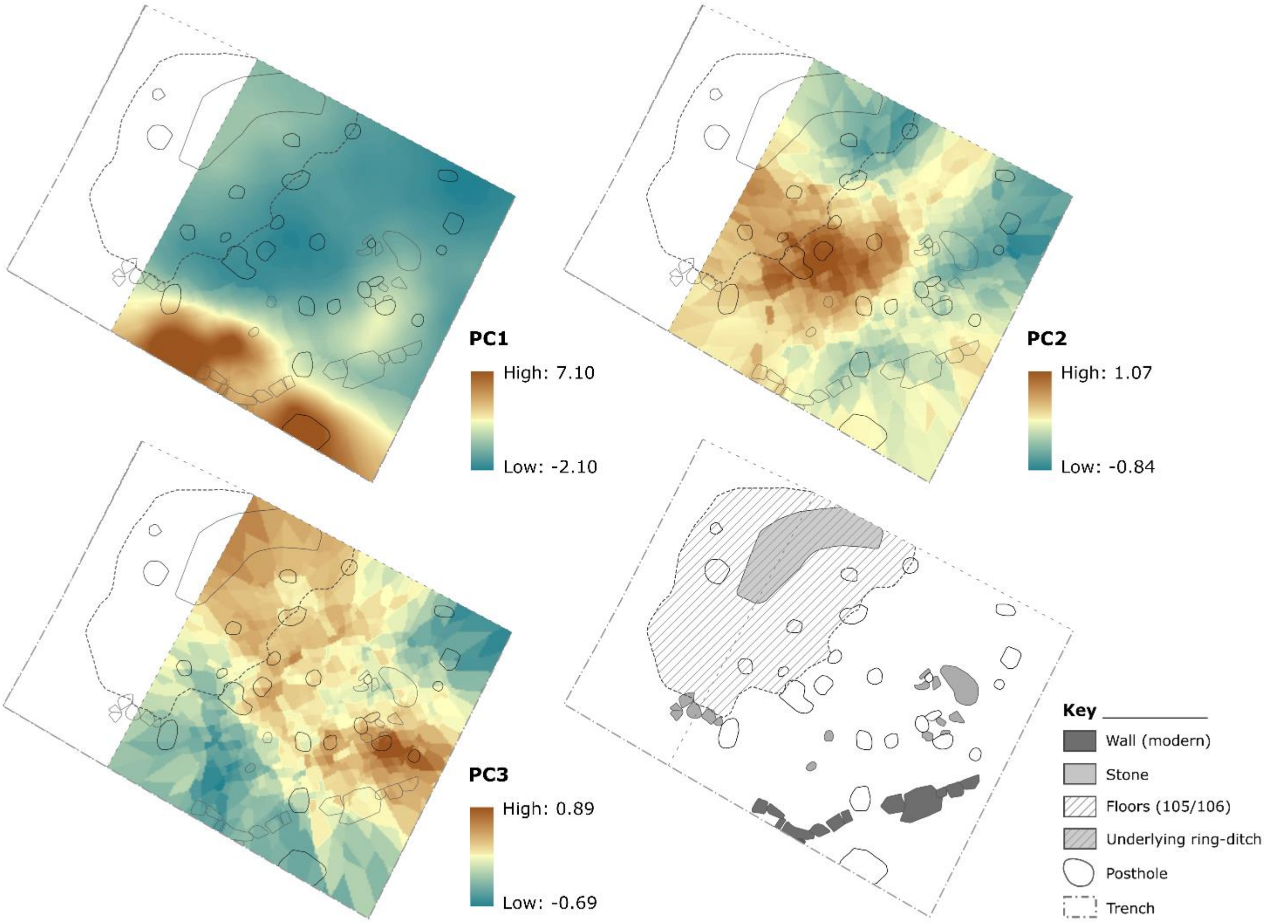

Fig. 7. Interpolation of Burghead upper surface principal component analysis (PCA) results – positive loadings brown, negative loadings blue – with feature map (bottom right) to aid interpretation. For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.

Although PC1 was dominated by this area of contamination, it also identified enrichment towards the east of the trench, and in the visible extent of surfaces 105 and 106 (Fig. 7). Notably, these areas showed little to no enrichment in Cl, Cu, Ni or V, and no coal, clinker or slag was recovered from these areas during microrefuse analysis, suggesting their geochemical signatures were not associated with the later waste material. Instead, they correlated with elevated charcoal concentrations and likely reflected anthropogenic activity related to the structure and the concentration of postholes in the east (Supplementary Material 2).

The spatial distribution of PC2 corresponded to the area between the two non-contaminated areas identified in PC1 and had very few indications of habitation, returning some of the lowest values for magnetic susceptibility, organic matter content and plant macronutrients (Ca, P, S), alongside a comparative lack of charcoal (Figs. 7 and 8). PC3 further differentiated surface 105 and the eastern posthole area identified in PC1.

Fig. 8. Selected spatial results from Burghead upper surface single variable analysis; distributions of modern waste material, percent organic matter (loss-on-ignition at 550°C), magnetic susceptibility, and percent elements Ca (calcium), Cu (copper), Fe (iron), P (phosphorus) and S (sulphur) – results sorted according to natural breaks (Jenks)

4.2. Burghead lower surface (containing 106)

4.2.1. PCA results

Four principal components were chosen for analysis according to the Kaiser criterion (Kaiser, 1960, 1970) and accounted for 72.87% of the total variance of the geochemical record (Table 2).

Table 2. Results of the first four principal components for Burghead lower surface, showing loadings and % of the variance explained

Components	PC1	PC2	PC3	PC4
pH	-0.57	0.02	0.70	0.13
EC	0.71	-0.11	-0.61	-0.01
LOI	0.94	-0.15	0.03	0.05
Magnetic susceptibility	0.82	-0.08	0.00	0.12
Al	0.44	0.74	-0.10	0.10
Ba	0.22	0.50	0.17	-0.29
Ca	0.87	-0.09	0.33	-0.03
Cr	0.51	0.12	-0.16	-0.48
Fe	0.89	-0.09	0.03	0.06
K	0.03	0.91	-0.09	0.09
P	0.78	0.08	0.20	-0.08
Rb	0.40	0.48	0.14	0.13
S	0.89	-0.10	-0.07	-0.01
Si	-0.71	0.40	-0.18	0.30
Sr	0.76	0.06	0.37	-0.17
Ti	0.85	0.07	0.03	0.30
Zr	0.41	-0.18	0.00	0.66
% variance	46.78	12.48	7.57	6.04
Accumulative %	46.78	59.26	66.83	72.87

The first principal component (PC1) accounted for 46.78% of the total variance and appeared to reflect areas with a higher organic content and lower mineral component, demonstrating high positive loadings (>0.70; Table 2) for nine of the variables, and negative loadings (>-0.55) for Si and pH (Fig. 9). The positively correlated elements included common indicators of human habitation such as Ca, P, and elevated magnetic susceptibility – the latter indicating the presence of particles which had been magnetically enhanced by heating (Milek & Roberts, 2013, p. 1853; Bintliff & Degryse, 2022). Strong positive loadings (>0.70) for EC, LOI, plant macronutrients (Ca, P and S) and groundwater trace elements (Sr) reflected an increased organic component that could result from the deposition of plant or wood materials or their ashes (Wilson et al., 2005; Davidson et al., 2007; Entwistle et al., 2007; Jones et al., 2010; Bintliff & Degryse, 2022). This was corroborated by a strong negative loading (>-0.71) for Si (the primary mineral component of sand), however the accompanying positive correlation for Ti complicates the interpretation. Titanium is a natural weathering product of silicate rock and is generally indicative of a high mineral content rather than anthropogenic inputs (Knudson et al., 2004, p. 451).

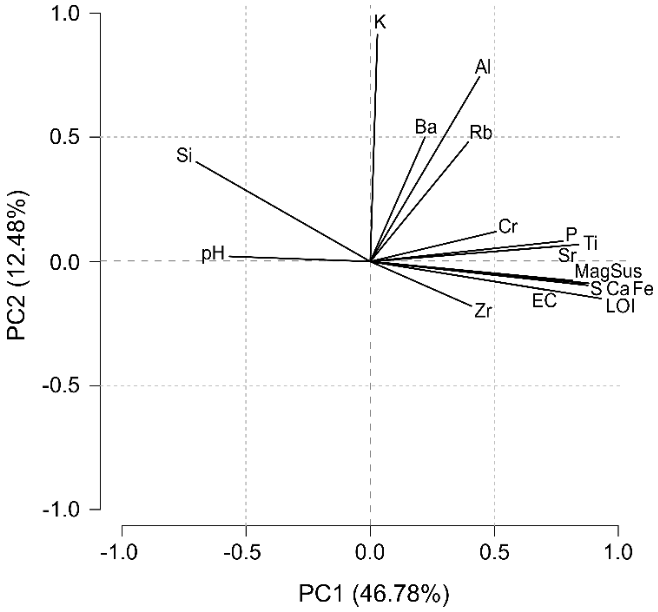

Fig. 9. Results of the first two principal components (lower surface)

PC2 demonstrated moderate to high loadings (0.40–0.91) for lithogenic elements (Al, Ba, K, Rb, Si) and most likely captured the natural variability of elements in Burghead's quartz and feldspar sands (Benton et al., 2002, p. 31–41). PC4 also demonstrated positive loadings for elements associated with the weathering of silicate rock (Si, Ti, Zr) that appeared to reflect the local sandstone geology (Garcia et al., 1994). PC3 demonstrated the inverse relationship between pH and EC, in which areas of lower pH typically had a higher nutrient/soluble salt concentration.

4.2.2. Spatial distributions

The positively correlated elements of PC1 appeared to capture localised anthropogenic enrichment associated with the identifiable extent of floor layer 106 (Fig. 10). The suite of variables included elevated magnetic susceptibility and plant macronutrients, which may suggest the presence of soil-rich organic deposits, such as peat or turf, that decomposed/burnt *in situ*. Alternatively, it could indicate their use as fuel sources whose ash was subsequently spread across the structure interior (Nesbitt et al., 2013, p. 14). Distribution maps of the elements excluded from statistical analysis showed that this area was also enriched in Zn (another organic matter indicator), and moderately correlated with concentrations of charcoal (Fig. 11).

An additional area of anthropogenic enrichment was identified by PC1 in the southwest corner of the trench and correlated with the highest concentration of charcoal recovered from the lower surface. Its location may indicate an extension of surface 106 or represent the remains of a burnt and degraded turf wall (as suggested by the field evidence from the 2017 trench – Fig. 3). The moderate negative loading of pH showed that these areas were among the most acidic on the site.

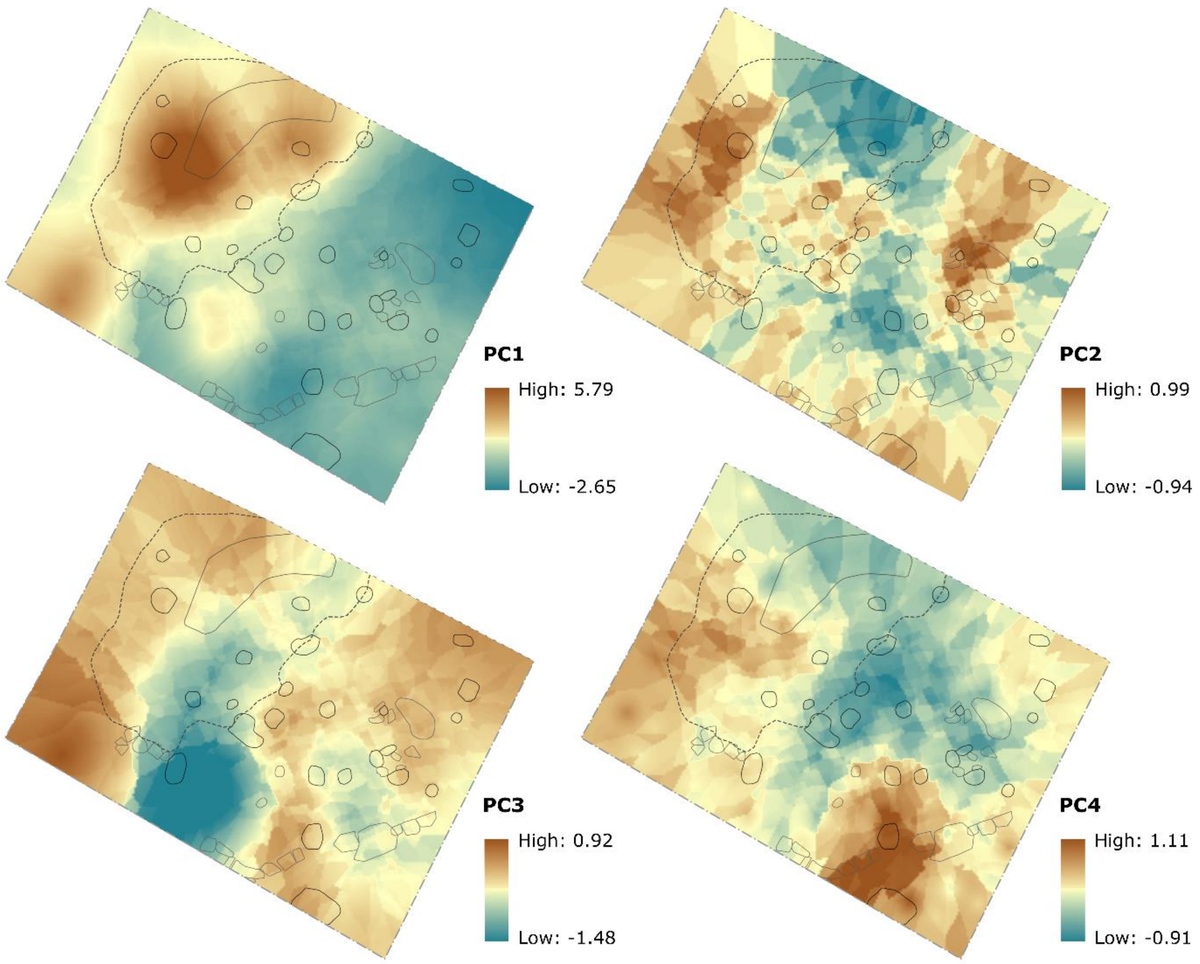

Fig. 10. Interpolation of Burghead lower surface principal component analysis (PCA) results – positive loadings brown, negative loadings blue. For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.

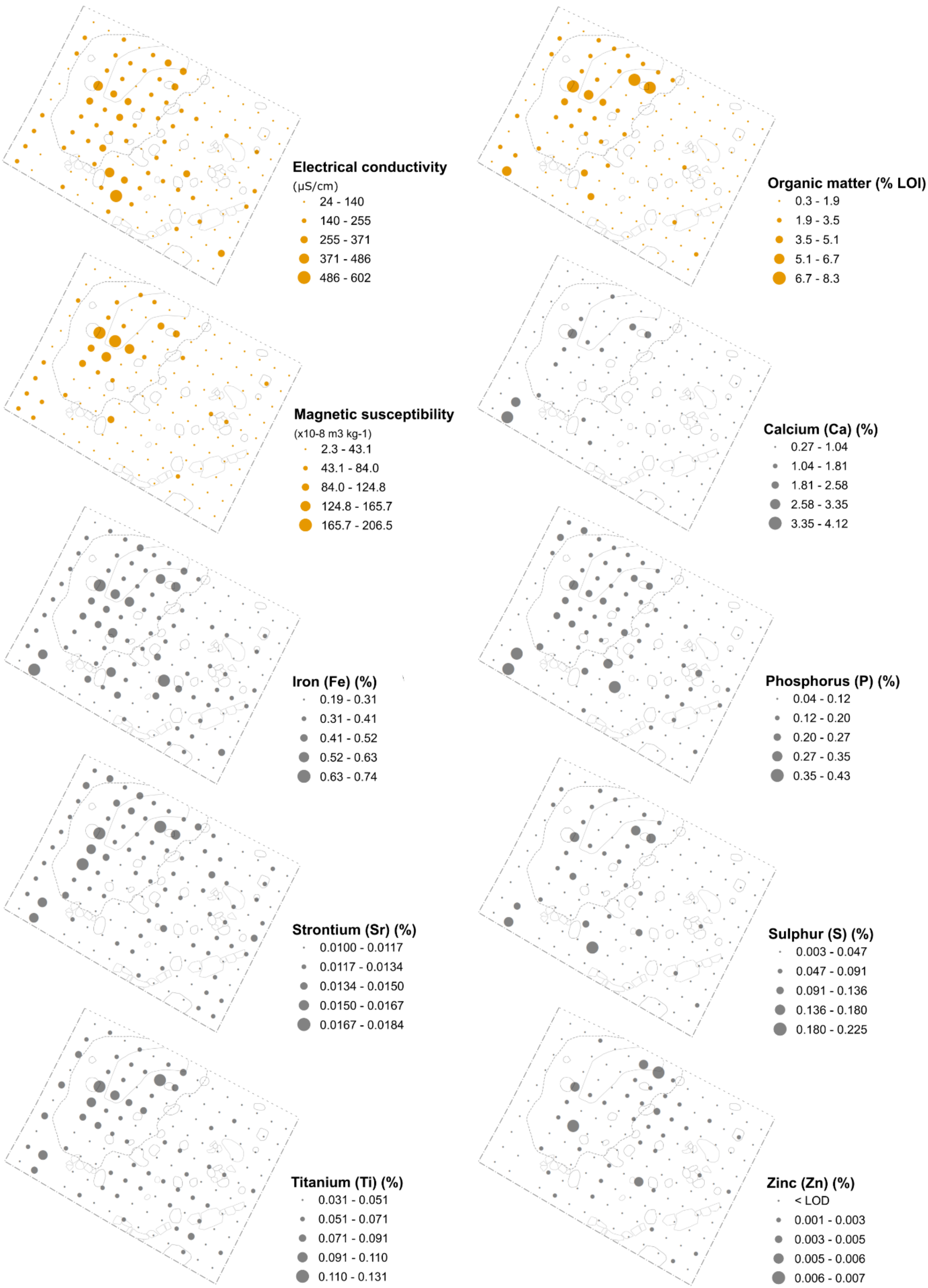

Fig. 11. Selected spatial results from Burghead lower surface single variable analysis; distributions of electrical conductivity (EC), percent organic matter (loss-on-ignition at 550°C), magnetic susceptibility, and percent elements Ca (calcium), Fe (iron), P (phosphorus), Sr (strontium), S (sulphur), Ti (titanium) and Zn (zinc) – results sorted according to equal intervals

Ten of the 13 elements subjected to statistical analysis showed positive correlations with EC that were statistically significant at the 0.01 level (Supplementary Material 3). However, only the element distribution maps of S and Fe (and to a lesser extent Ca) corresponded to the pattern of EC elevation observed in the south of the trench (Figs. 10 and 11 – PC3, negative loading, dark blue colour). Nutrients are prone to leaching, particularly in free-draining soils with coarse texture, such as sands. Given that Fe and S were the most highly elevated elements within this area of the upper surface, the relationship likely relates to leaching from the overlying contamination (Lehmann & Schroth, 2003).

4.3. Burghead micromorphology

4.3.1. Surfaces 105/106

Thin-sections BHF16-C and BHF16-D were taken from a baulk across the structure to investigate preservation and composition of the surfaces believed to be floors. Both the upper (105) and lower surfaces (106) had been extensively illuviated and bioturbated, with any evidence of a relic floor surviving only as intergrain microaggregates (created by soil fauna) and organic coatings of the quartz and feldspar sand grains (produced by illuviation – downward movement of organic matter) (Table 3; detailed descriptions, section drawings and interpretations in Supplementary Material 1). Organic matter and microaggregate concentrations decreased down the profile, and neither context contained anthropogenic inclusions other than trace charcoal. These layers were interpreted as remnants of relic occupation deposits and evidence of extremely poor stratigraphic preservation within this area of the site.

4.3.2. Western trench edge

The two thin-sections taken from the western trench edge, samples BHF16-A and BHF16-B, also captured the upper and lower surfaces however the upper surface had a markedly different composition and preservation (Fig.12). A high degree of illuviation and bioturbation was still evidenced by earthworm channels, organic coatings and intergrain microaggregates however context 105 was found to be rich in microartefacts. The layer had the highest charred organic matter content of any sample taken at the site (5-10%), with larger and more frequent fragments of charcoal that included pine (*Pinus sp.*), charred monocot stems and a charred cereal grain. The upper floor also contained wood ash in the form of aggregates of silt-sized calcium carbonate, and several aggregates of grey clay that had a platy microstructure, parallel and subparallel planar voids (10% porosity), and a unistriated b-fabric. The clay was also found coating a large charcoal fragment (4 x 21 mm) that may be evidence of charred wattle-and-daub, with the unistriated b-fabric and planar voids resulting from a 'smearing' action (Milek & French, 2007, p. 338; Friesem et al., 2017, p. 104–106) (Fig. 13, c and d). Anthropogenic inclusions were unique to this thin-section and layer and were unusually well preserved given the extensive illuviation and bioturbation throughout. This may reflect the more favourable preservation identified in the 2017 trench or represent increased anthropogenic activity towards the end of the structure associated with the hearth. It may also be evidence of a contemporary wattle partition or wall-panelling that burnt *in situ*.

The parts of context 106 captured in samples A and B on the western trench edge were similar to those captured in the baulk, in that they contained no anthropogenic inclusions other than trace charcoal and decreased in organic matter and microaggregate concentrations down the profile. One notable difference was the inclusion of two different fabric types. Fabric 1 comprised localised aggregates of yellowish-brown clayey-silt with massive microstructure and speckled b-fabric. Fabric 2 existed as discrete aggregates and intercalations (around 1 mm thick) of loamy sand with very angular quartz grains and undifferentiated b-fabric (Fig. 13, e). As with the inclusions in 105, these were only captured in the samples taken from the western trench edge, and although their precise origin is unknown, they represent anthropogenically-deposited mineral materials.

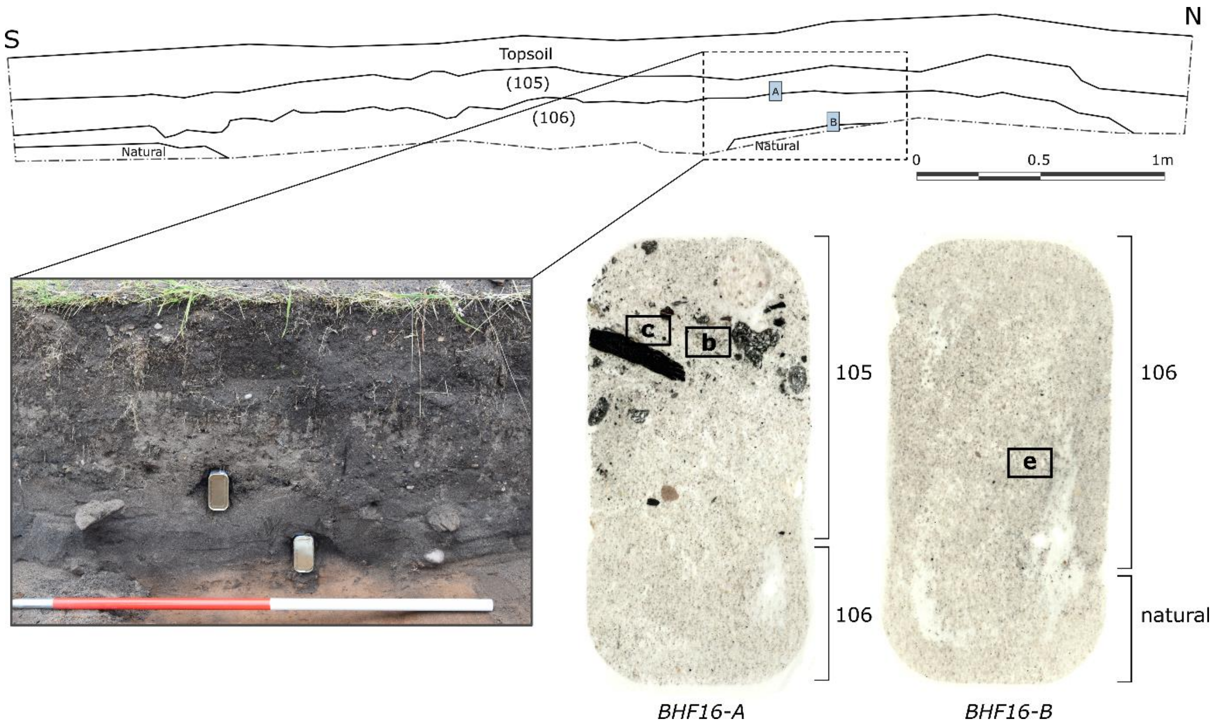

Fig. 12. Scans of Burghead thin-sections BHF16-A (centre) and BHF16-B (right) with photograph of soil blocks in section (left) and section drawing (top) showing sampled stratigraphy and location of photomicrographs in Fig. 13

4.3.3. Eastern area

Thin-sections BHF16-E, BHF16-F and BHF16-G were taken from the area east of the visible layer 106 to investigate whether the lower surface continued, had been truncated by later activity, or represented different trampling practices. All three had a similar composition to the other examples of 106, displaying a highly illuviated and bioturbated surface containing intergrain microaggregates with no surviving microstructure of a relic floor and no anthropogenic inclusions other than trace charcoal. The only apparent difference was the quantity of amorphous organic matter; BHF16-E and BHF16-G were comparable with the values recovered from the visible floor (2-5%), whereas BHF16-F had significantly fewer microaggregates and less amorphous organic matter (<1%). Given the limited field, geochemical and micromorphological evidence, there is no evidence that these deposits represent a continuation of the lower floor 106.

Table 3. Summary of descriptive sediment attributes, inclusions and post-depositional alterations at Burghead

	Structure			Void Types*			Fine Material			Organic Matter		Inclusions				Pedofeatures	
Slide/unit	Textural class	Microstructure	Course:fine (100μm) ratio	Channels	Simple packing voids	Complex packing voids	Nature of fine material (PPL)	Colour of fine material (OIL)	Birefringence fabric (XPL)	Charred	Uncharred	Wood ash	Aggregates (clay)	Aggregates (other)	Rubified fine material	Fe/Mn	Excremental
A 105	Medium-course sand	Intergrain microaggregate	92:8	▪▪▪▪▪		▪▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Very dark brown; black	Undifferentiated	▪▪▪▪	▪▪	▪	▪▪		▪	+	▪▪
A 106	Medium-course sand	Intergrain microaggregate	96:4	▪▪▪▪▪	▪	▪▪▪▪▪▪▪▪▪▪	Brown; dark brown; dotted	Dark brown	Undifferentiated	+	▪▪			▪		+	▪▪
B 106	Medium-course sand	Intergrain microaggregate	98:2	▪▪▪▪▪	▪▪	▪▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Very dark brown; black	Undifferentiated	▪	▪			▪▪	+		▪
C 105	Medium-course sand	Intergrain microaggregate; localised pellicular	93:7	▪▪▪▪	▪	▪▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Very dark brown; black	Undifferentiated	▪	▪▪						▪▪
C 106	Medium-course sand	Intergrain microaggregate; localised pellicular	97:3	▪▪▪▪	▪▪▪▪	▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Very dark brown; black	Undifferentiated	▪▪	▪▪				+	+	▪
D 105	Medium-course sand	Intergrain microaggregate; localised pellicular	93:7	▪▪▪▪	▪▪	▪▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Very dark brown; black	Undifferentiated	▪	▪▪▪						▪▪▪
D 106	Medium-course sand	Intergrain microaggregate; localised pellicular	97:3	▪▪▪▪▪	▪▪▪▪	▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Very dark brown; black	Undifferentiated	▪	▪▪						▪▪
E 106**	Medium-course sand	Intergrain microaggregate; localised single-grain	97:3	▪▪▪	▪▪▪▪▪▪▪▪	▪▪▪▪▪▪	Dark brown; dotted	Dark brown	Undifferentiated	+	▪▪						▪▪
F 106**	Medium-course sand	Single-grain; localised intergrain microaggregate	99:1	▪▪	▪▪▪▪▪▪▪▪	▪▪▪▪▪▪▪	Dark brown; dotted	Dark brown	Undifferentiated	+	▪						▪
G 106**	Medium-course sand	Intergrain microaggregate	96:4	▪▪▪▪	▪▪▪▪	▪▪▪▪▪▪▪▪▪▪	Dark brown; dotted	Dark brown	Undifferentiated	+	▪▪						▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* void frequency refers to % total void space (following Bullock et al. 1985; Stoops 2021: 73)
** labelled as (106) during excavation but do not represent an extension of the lower floor (106)

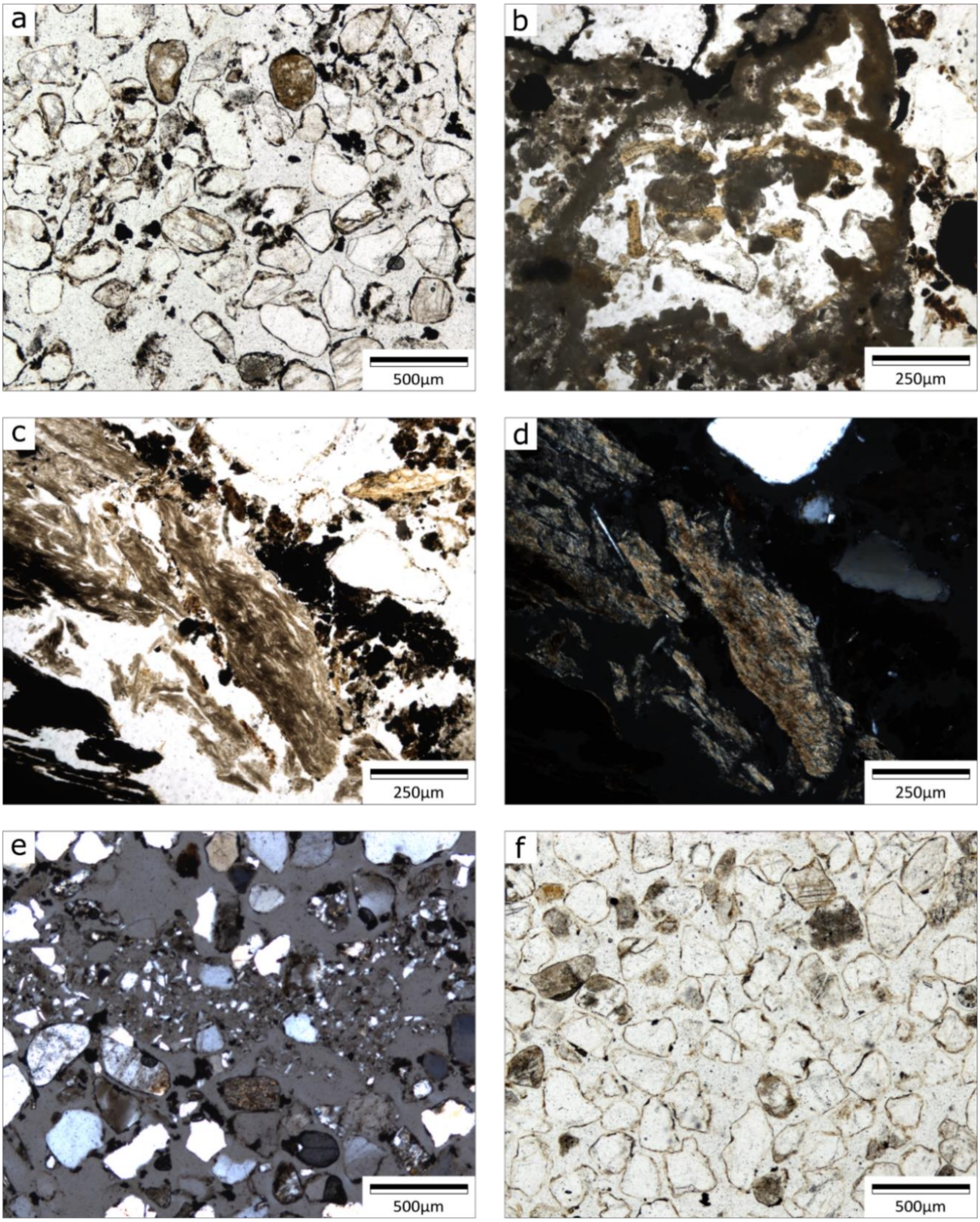

Fig. 13. Photomicrographs of Burghead thin-sections, (a) BHF16-C, context 106, showing intergrain microaggregate structure of relic floor (PPL); (b) BHF16-A, context 105, showing wood ash in the form of aggregates of micrite and poorly preserved bone fragments (PPL); (c) BHF16-A, context 105, showing clay daub fragment with platy microstructure, parallel and subparallel planar voids (PPL); (d) as previous, showing unistriated b-fabric (XPL); (e) BHF16-B, context 106, showing Fabric 2 intercalation (partial XPL); (f) BHF16-F, single-grain microstructure with localised intergrain microaggregate demonstrating lack of amorphous organic material in comparison with (a) (PPL).

4.4. Dunnicaer

Despite the small excavation area at Dunnicaer, the distribution maps and statistical correlations indicated variability and clustered distribution patterns within Dunnicaer's lower terrace. There was a clear positive correlation (r_s up to 0.87) between Ba, Ca, Mn, P, Sr and Zn that related to the area in and immediately north of the hearth (Tables 4 and 5; Fig. 14). Elevation in these particular elements has been demonstrated in midden and hearth areas of settlements elsewhere in Scotland, comprising trace elements and plant macronutrients most often linked to the decomposition or burning of plant matter and excreta (Entwistle et al., 1998; Wilson et al., 2005, 2008; Davidson et al., 2007; Bintliff & Degryse, 2022). Mn and Zn have more specifically being linked to animal dung and manure, perhaps indicating its use as a fuel source (Ottaway & Matthews, 1988; Bintliff & Degryse, 2022, p. 4). Elevations in Ca and Sr have been argued to derive from the specific inclusion of bone waste, and broadly correlated with the distribution of burnt bone observed at Dunnicaer (with both returning the highest values in the northeast trench corner) (Knudson et al., 2004, p. 449; Nielsen & Kristiansen, 2014).

Table 4. Most highly correlated variables (r_s >0.70)

Variables		**Correlation Coefficient**
LOI	S	0.91
Ca	Sr	0.87
Ba	Mn	0.86
Ba	Zn	0.81
Mn	Zn	0.79
LOI	K	-0.79
K	Ti	0.78
LOI	Si	-0.77
Si	Ti	0.77
LOI	Ti	-0.73
Al	K	0.73
K	S	-0.72
S	Si	-0.71
K	Si	0.71

Whilst the overall pH range was narrow (4.1–5.5), samples collected from the hearth and surrounding deposits were the least acidic (pH 5.1–5.5) and corresponded to elevated EC values, indicating very high nutrient or soluble salt levels associated with the deposition of ash. Though the suite of elements mentioned above were elevated in this area, the correlation coefficient (r_s) only showed a strong positive correlation for EC with Cu and Zn, which was statistically significant at the 0.01 level (Table 5). Charcoal and bone are believed to play a role in both the loading and post-depositional retention of Ca, Sr, P, Zn, and Cu, suggesting that the soil element

Table 5. Dunnicaer correlation analysis based on Spearman's rho (r_s) for geochemical and multi-element values

	pH	EC	LOI	Mag Sus	Al	Ba	Ca	Cl	Cr	Cu	Fe	K	Mg	Mn	P	Pb	Rb	S	Si	Sr	Ti	V	Zn	Zr
pH	1.00																							
EC	0.12	1.00																						
LOI	-0.66**	-0.10	1.00																					
Mag Sus	-0.20	0.33	0.34	1.00																				
Al	0.31	-0.41*	-0.50*	0.03	1.00																			
Ba	0.05	0.48*	0.03	0.54**	-0.12	1.00																		
Ca	0.52**	0.29	-0.33	0.22	0.19	0.65**	1.00																	
Cl	-0.63**	0.09	0.54**	0.46*	-0.21	0.00	-0.31	1.00																
Cr	0.04	0.07	0.05	0.13	0.18	0.23	0.09	-0.18	1.00															
Cu	-0.12	0.64**	0.30	0.56**	-0.34	0.57**	0.27	0.20	0.31	1.00														
Fe	-0.15	-0.19	0.40	0.57**	0.28	0.17	0.08	0.47*	0.29	0.18	1.00													
K	0.44*	-0.19	-0.79**	-0.37	0.73**	-0.17	0.29	-0.41*	0.13	-0.38	-0.10	1.00												
Mg	0.45*	0.00	-0.51*	-0.14	0.41*	-0.12	0.08	-0.29	0.07	0.11	-0.04	0.54**	1.00											
Mn	0.08	0.44*	0.14	0.70**	-0.05	0.86**	0.62**	0.02	0.38	0.62**	0.31	-0.24	-0.21	1.00										
P	-0.22	0.13	0.54**	0.57**	-0.25	0.66**	0.35	0.26	0.29	0.50*	0.56**	-0.51*	-0.41*	0.69**	1.00									
Pb	0.22	0.51*	-0.33	0.14	0.22	0.30	0.39	-0.11	0.24	0.45*	-0.05	0.30	0.44*	0.15	-0.04	1.00								
Rb	-0.37	-0.40	0.45*	-0.11	0.00	-0.35	-0.45*	0.22	0.14	-0.21	0.25	-0.08	-0.18	-0.26	0.13	-0.42*	1.00							
S	-0.56**	-0.18	0.91**	0.35	-0.32	0.05	-0.25	0.52**	0.09	0.26	0.54**	-0.72**	-0.53**	0.19	0.66**	-0.34	0.47*	1.00						
Si	0.42*	-0.29	-0.77**	-0.53**	0.58**	-0.26	0.05	-0.59**	-0.12	-0.57**	-0.42*	0.71**	0.47*	-0.35	-0.65**	0.09	-0.17	-0.71**	1.00					
Sr	0.55**	0.20	-0.43*	0.17	0.36	0.45*	0.87**	-0.37	0.03	0.24	0.10	0.37	0.22	0.48*	0.22	0.39	-0.54**	-0.28	0.10	1.00				
Ti	0.39	-0.10	-0.73**	-0.55**	0.51*	-0.38	0.02	-0.26	-0.13	-0.47*	-0.28	0.78**	0.51*	-0.55**	-0.69**	0.35	-0.15	-0.67**	0.77**	0.05	1.00			
V	-0.05	-0.12	-0.05	0.47*	0.54**	-0.03	-0.05	0.33	0.21	0.01	0.66**	0.26	0.02	0.10	0.12	0.09	0.14	0.08	-0.15	0.11	-0.02	1.00		
Zn	0.16	0.60**	-0.28	0.56**	0.04	0.81**	0.70**	0.03	0.22	0.57**	0.10	0.13	0.04	0.79**	0.35	0.39	-0.48*	-0.25	-0.13	0.57**	-0.13	0.13	1.00	
Zr	-0.17	0.01	-0.08	-0.06	-0.08	0.11	0.00	0.07	0.04	0.04	-0.28	-0.04	-0.20	0.13	-0.05	-0.25	-0.10	-0.06	0.09	-0.07	-0.13	-0.05	0.18	1.00

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

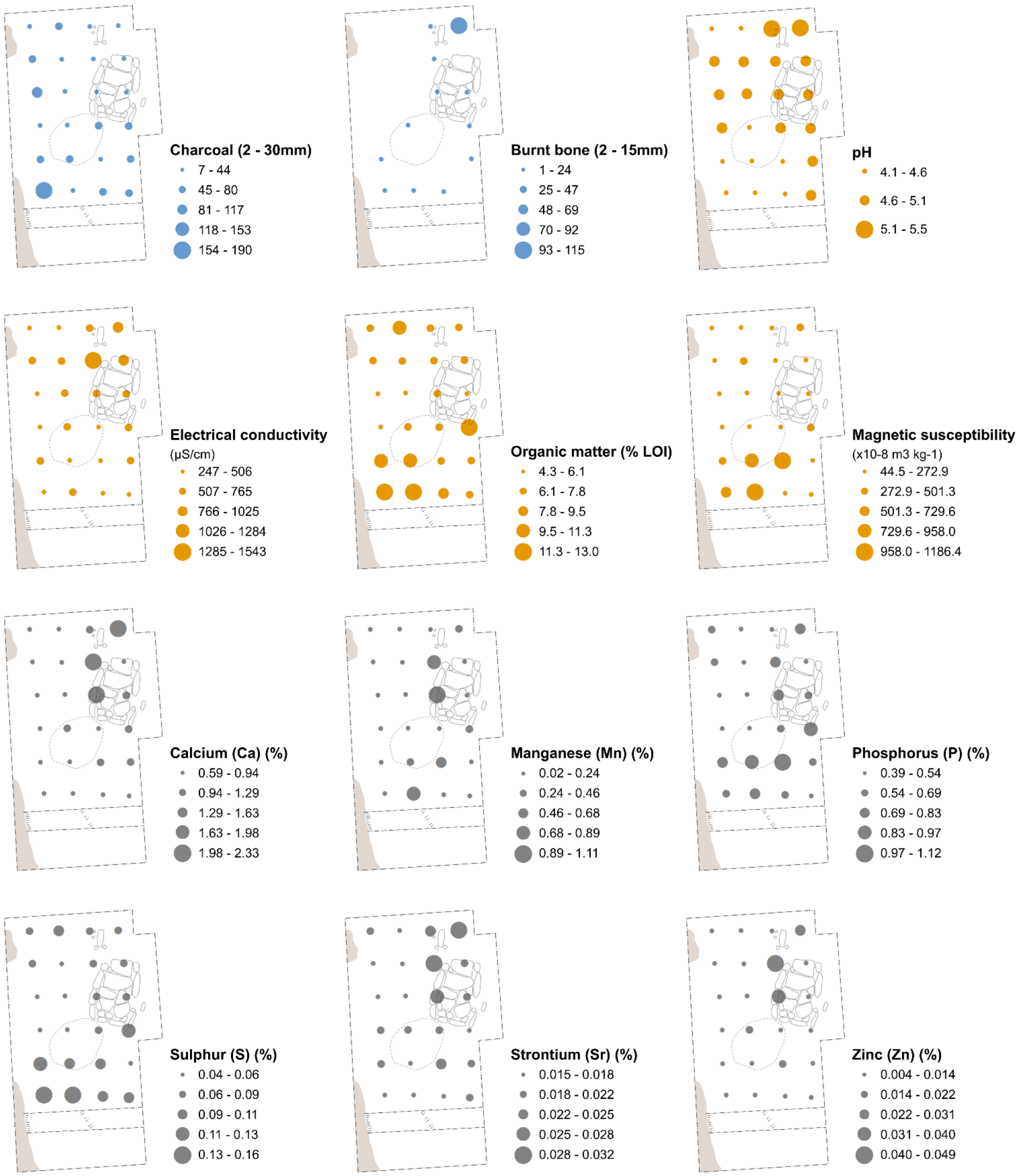

Fig. 14. Selected results from Dunnicaer spatial analysis – distributions of charcoal, burnt bone, pH, electrical conductivity (EC), percent organic matter (loss-on-ignition at 550°C), magnetic susceptibility and percent elements Ca (calcium), Mn (manganese), P (phosphorus), S (sulphur), Sr (strontium) and Zn (zinc).

concentration patterns within this area are likely related to these hearth residues (Davidson et al., 2007; Wilson et al., 2008).

Elevated organic matter content was observed in the southwest corner of the trench, correlating positively (r_s up to 0.91, p = 0.01) with plant macronutrients P and S, and to some extent magnetic susceptibility and Mn, and negatively (r_s >-0.72, p = 0.01) with lithogenic elements K, Si and Ti (Table 5; Fig. 11). It is notable that the highest values of magnetic susceptibility were not recorded in/around the hearth itself but were more closely associated with the southern edge of the trench and the charcoal patch 1007, which was interpreted in the field as hearth rake-out. The magnetic enhancement of this area indicates the presence of soil particles, pebbles and/or iron nodules that were affected by heating (Milek & Roberts, 2013, p. 1853). This suggests that heated soil material from the base of the hearth may have mixed with ash residues, and perhaps also signals the use of soil-rich fuel sources such as peat or turf (Milek & Roberts, 2013, p. 1853; Nesbitt et al., 2013, p. 14). That the highest acidity levels were observed in the areas associated with context 1007 is surprising, given that wood ash is alkaline (pH 9–13.5) and would be expected to neutralise the acidity of the organic soil to some extent (Etiégni & Campbell, 1991; Karkanas, 2021).

There was a comparative depletion in habitation indicators in the area east of the hearth that correlated with elevations in the lithogenic elements Al, K, Si, Ti and Zr (Fig. 14; Supplementary Material 4). This area lay between areas of raised bedrock (Fig. 5) and marked the natural passage from the upper terrace to the lower terrace during excavation, perhaps having performed a similar function in the past. A hard-packed deposit of what appeared to be redeposited natural sat directly above the bedrock on the eastern edge of the trench and may have functioned as a levelling surface that became incorporated into the floor layers through repeated trampling.

4.5. Dunnicaer micromorphology

The three thin-sections taken from the lower terrace sondage contained layers related to occupation surfaces and the modification of the lower terrace. Four separate lenses were identified in floor 1009 (sub-contexts 1009.1 to 1009.4 – Fig. 15), all of which comprised sandy silt loams with a porphyric c/f related distribution, subangular blocky microstructure, 5-20% amorphous decomposed organic matter, and extensive staining by organic acid pigmentation.

Phytoliths were not readily identifiable in any of the layers and may have been masked by this staining.

Despite the lenses having been reworked by soil fauna, the horizontal orientation of charcoal and minerals was observable to varying degrees, with sub-context 1009.2 also containing a significant percentage of horizontal planar voids that result from vertical compaction (10-20%) (Table 6; Fig. 16). These are key indicators of trampling on occupation surfaces (see Rentzel et al., 2017), supporting the field interpretation of floor layers within the structure's interior. Lenses 1009.3 and 1009.4 retained an intra-aggregate crumb structure which likely related to the nature of the material used to form the surface. 1009.4 also contained multiple sublinear areas (max. 27 x 3 mm) of darker, more organic material with lower porosity, which may be evidence of compaction and/or the use of organic material such as turf (with the crumb structure a remnant from turf A horizons). Given that the preceding context (1011) related to the lower hearth, this likely represents a rebuilding episode contemporary with the construction of the new hearth.

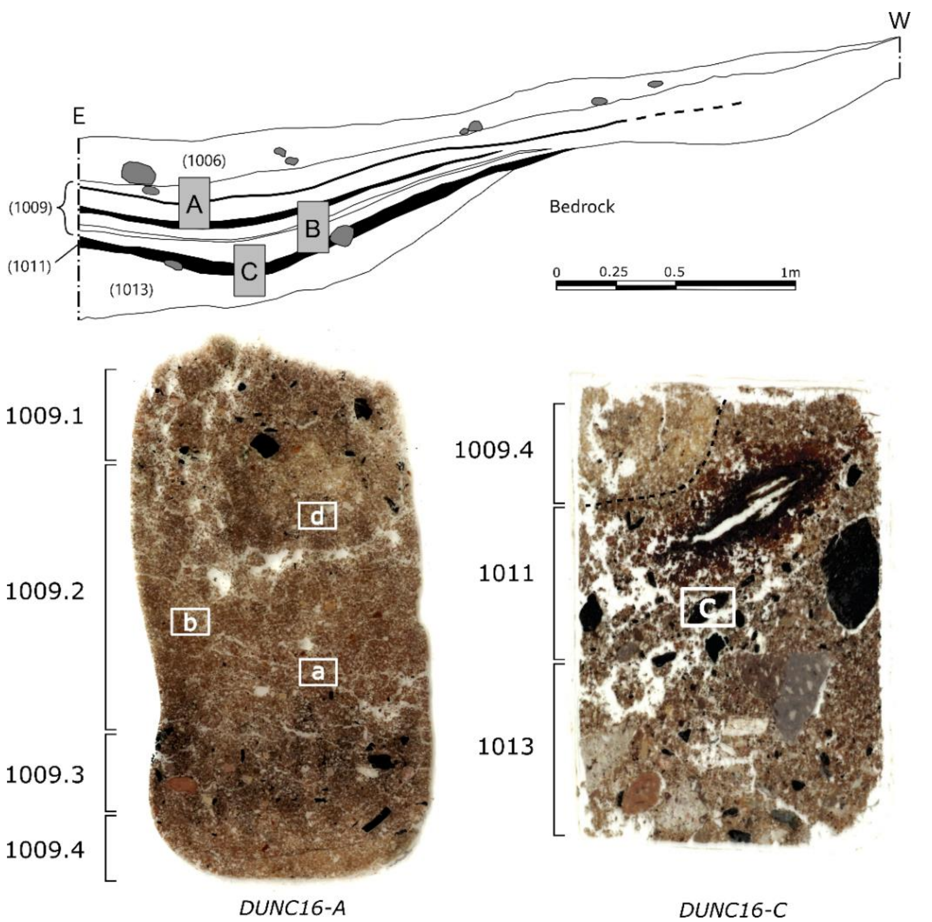

Fig. 15. Scans of Dunnicaer thin-sections DUNC16-A (left) and DUNC16-C (right) with section drawing (top) showing sampled stratigraphy, sub-contexts of 1009, and location of photomicrographs in Fig. 16

Table 6. Summary of descriptive sediment attributes, inclusions and post-depositional alterations at Dunnicaer

	Structure			Void Types*				Fine Material			Organic Matter		Inclusions		Pedofeatures	
Slide/unit	Textural class	Microstructure	Course:fine (100µm) ratio	Channels and vughs	Planar (random)	Planar (horizontal)	Compound packing voids	Nature of fine material (PPL)	Colour of fine material (OIL)	Birefringence fabric (XPL)	Charred	Uncharred	Intrusive aggregates	Rubified fine material	Fe/Mn	Excremental
A 1009.1	Sandy silt loam	Weakly to moderately developed subangular blocky with channels	55:45	▪▪▪▪▪▪▪▪▪▪	▪▪▪			Orangish-brown; dotted	Orangish-yellow	Stipple-speckled	▪▪▪▪	▪▪▪		▪	▪	▪▪
A 1009.2	Sandy silt loam	Moderately developed subangular blocky with channels and horizontal planar voids	40:60	▪▪▪▪▪▪▪▪▪	▪▪▪▪	▪▪▪▪	▪	Orangish-brown; mid-brown; dotted	Orangish-yellow; brownish-yellow	Stipple-speckled	▪	▪▪▪	+	+	▪	▪▪
A 1009.3	Organic sandy silt loam	Well-developed subangular blocky with intra-aggregate crumb structure and channels	35:65	▪▪▪▪▪▪▪	▪▪▪▪▪▪▪	▪	▪▪▪	Orangish-brown; dark brown; dotted	Yellowish-brown; dark brown	Stipple-speckled; localised undifferentiated	▪▪▪▪	▪▪▪▪			▪	▪▪
B 1009.4	Sandy silt loam	Moderately to well-developed subangular blocky with intra-aggregate crumb structure and channels	35:65	▪▪▪▪▪▪	▪▪▪▪▪▪▪▪		▪▪▪▪	Orangish-brown; dark brown; dotted	Yellowish-orange; dark brown	Stipple-speckled	▪	▪▪▪		+	+	▪▪
C 1011	Organic silt loam	Crumb with localised channels	55:45	▪▪▪▪▪	+		▪▪▪▪▪▪▪▪▪▪	Orangish-brown; dark brown; dotted	Brownish-yellow; dark brown	Stipple-speckled	▪▪▪▪▪	▪▪▪▪			▪▪▪▪▪▪	▪▪▪▪
C 1013	Sandy silt loam	Channels with localised subangular blocky structure	65:35	▪▪▪▪▪▪▪▪▪▪	▪▪			Orangish-brown; dotted	Brownish-yellow	Stipple-speckled	▪▪▪	▪▪		▪	▪	▪▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* void frequency refers to % total void space (following Bullock et al. 1985; Stoops 2021: 73)

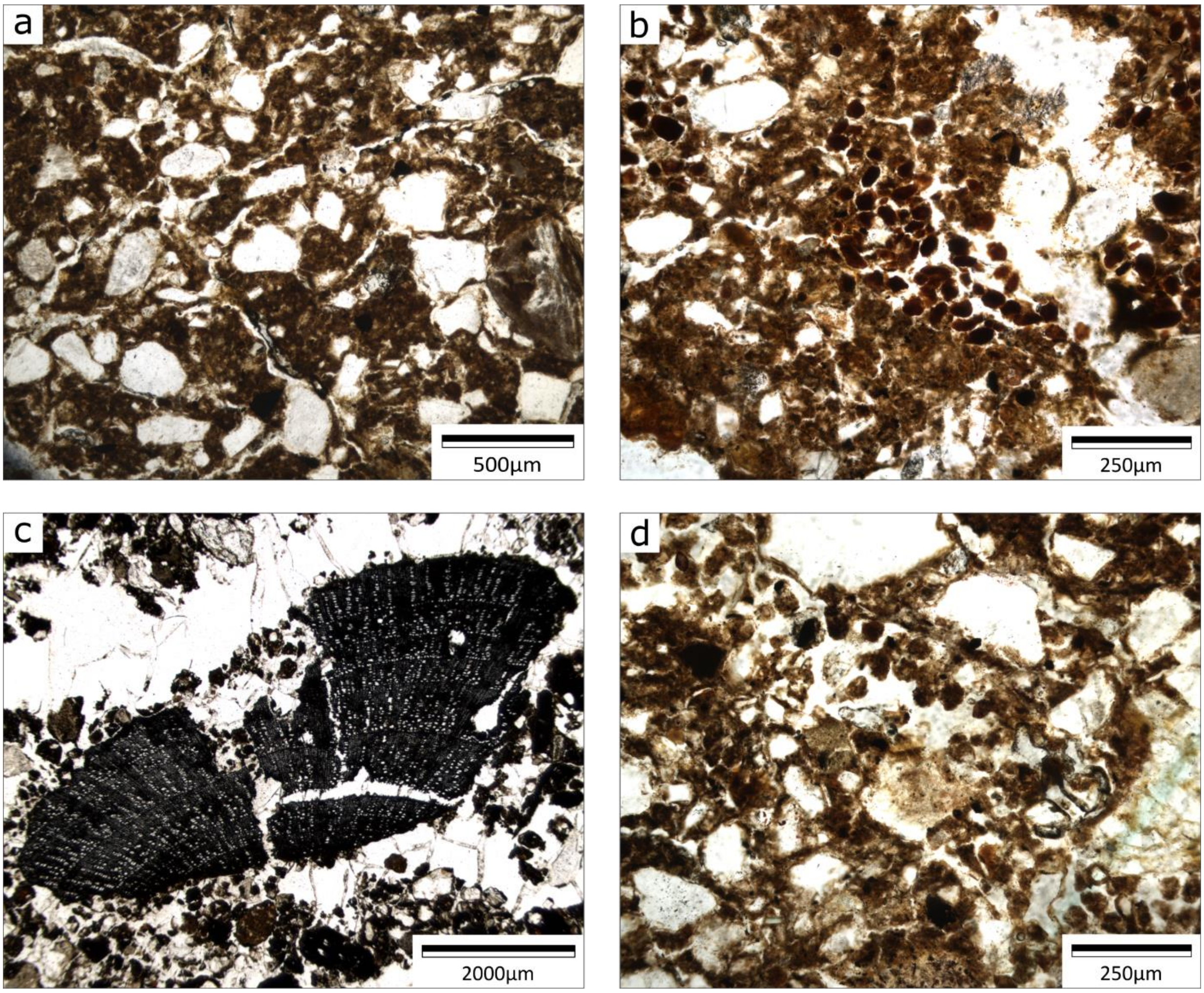

Fig. 16. Photomicrographs (PPL) of Dunnicaer thin-sections, (a) DUNC16-A, context 1009.2, showing subangular blocky microstructure and horizontal planar voids in a relic floor; (b) DUNC16-A, context 1009.2, showing heavily degraded organic nodules – possible leather item; (c) DUNC16-C, context 1011, showing 9 y/o hazel charcoal fragment; (d) DUNC16-A, context 1009.2, showing excremental pedofeatures in channel as evidence of bioturbation

The two thinnest lenses (1009.1 and 1009.3) were both 15 mm in depth and were significantly richer in charred material (10-20%). They appeared to alternate with thicker layers up to 75 mm in depth, perhaps indicating a maintenance practice that involved the treatment or sealing of well-worn floor deposits with ash. Although burnt bone was recovered during microrefuse analysis, none of the layers in context 1009 contained anthropogenic inclusions other than varying quantities of diffuse porous charcoal (1-10%) (Corylus sp. and Betula or Salix/Populus sp.). Lens 1009.2 did contain a cluster of strongly decomposed circular organic material which may represent something similar to degraded leather, however the extent of decomposition meant that it was not possible to explore this further (Fig. 16, b). Quantities of rubified iron nodules characteristic of peat and turf ash were only present in trace or very low amounts (<2%).

Sample DUNC16-C captured the floor (1011) associated with the lower hearth. A large earthworm channel and Fe plant pseudomorph restricted the space available for analysis (Fig. 15), however the shallowness of this deposit in comparison to the cumulative lenses of 1009 was notable – particularly given the evidence for the lower hearth's extensive use (Noble et al., 2020, p. 284). This is perhaps evidence of different maintenance practices relating to the lower hearth, or the removal of cumulative layers prior to the building of the new hearth. As with 1009, no anthropogenic inclusions other than charcoal (*Betula or Salix/Populus sp. and Corylus sp.*) and plant matter were identified within the layer. DUNC16-C also identified the first archaeological layer, lying directly above the subsoil or bedrock, which comprised a sandy silt loam and angular gravel-sized rock fragments (up to 1.5 cm in size). This was likely deposited during the primary construction of the structure in order to level the lower terrace hollow and create a suitable occupation surface or foundation for a structure.

5. Discussion

5.1. Burghead

The most obvious anthropogenic signature at Burghead was an area of modern contamination in the upper surface (Fig. 17). The geochemical data and interpolated PCA confined the extent of its impact to the southern end of the trench, indicating that the surrounding material was more 'authentically' archaeological in nature. They also permitted a characterisation of modern industrial waste containing coal, clinker, cinder and slag, which was differentiated from archaeological material by an up to ten-fold increase in element concentration and, more specifically, the presence of Cl, Cu, Ni and V. Leaching into the lower layer can be attributed to the free-draining character of the sediments and the high-degree of illuviation observed in thin-section (Fig. 18).

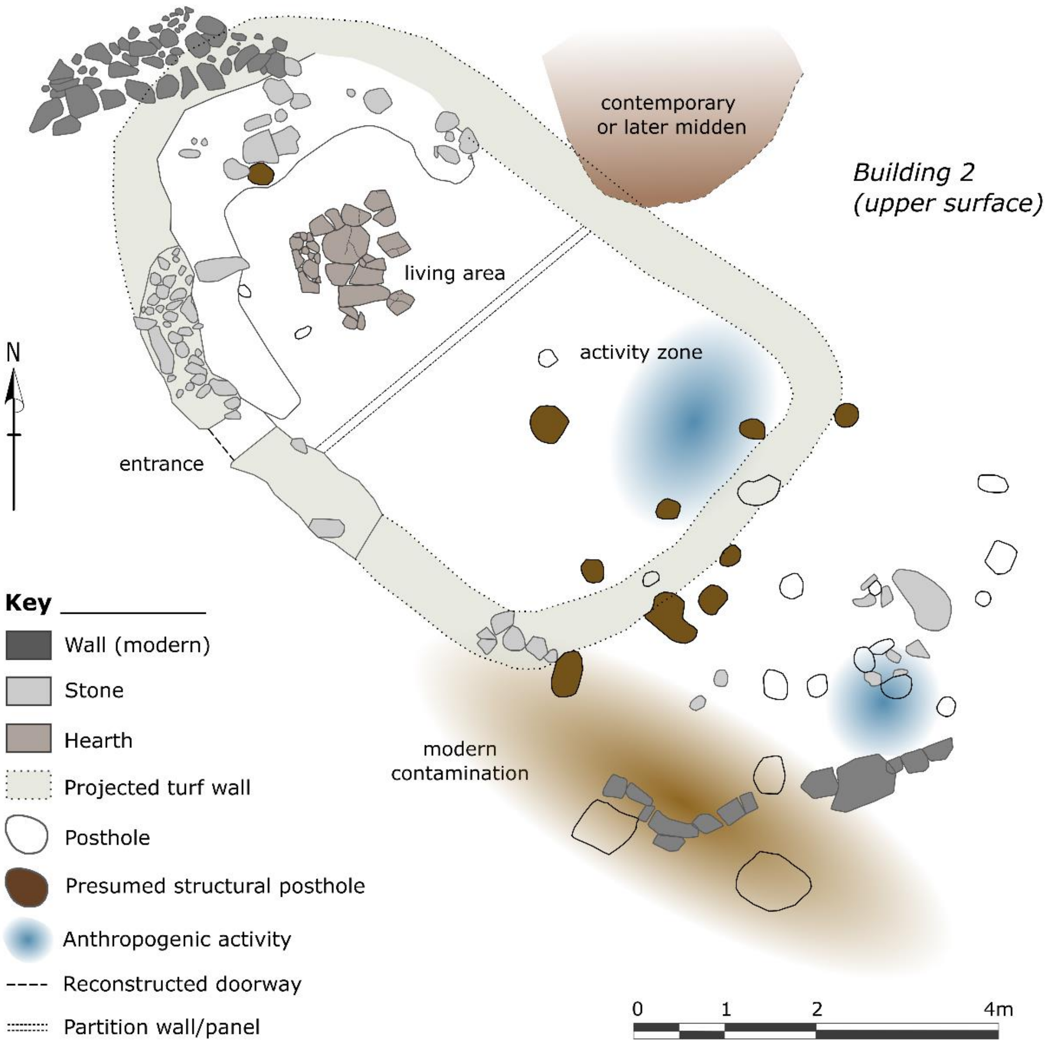

Fig. 17. Interpretive plan of Burghead upper surface, based on integrated field, microrefuse, geochemical and micromorphological evidence. For interpretation of the colour in this figure and legend, the reader is referred to the web version of this article.

The visible extents of surfaces 105 and 106, which were identified during excavation, were reflected in the geochemical data, most convincingly in the analysis of the lower surface which was characterised by enhanced soluble salt concentrations, magnetic mineral signatures, and chemical elevations associated with organic matter. This appeared to represent the remains of a decomposed burnt turf wall and/or an organic floor that may have had soil-rich ash spread across the structure interior. The practice of spreading ash is known from 10th-century Iceland (Milek & Roberts, 2013), post-medieval Scottish crofts (Smith, 1996; Nesbitt et al., 2013) and 19th/20th-century ethnography (Fenton, 1978, p. 195; Milek, 2012), where the floors of turf houses were treated to absorb moisture and odours. Recent evidence from a comparative geoarchaeological study at Lair in Glen Shee (central Scotland) suggests that this was also practiced on 7th to 9th century Pictish farmsteads (Reid et al., forthcoming). Though geochemical signatures in the upper surface were dominated by contamination, a pattern of element enrichment also seemed to respect the eastern end of 105 and 106.

Micromorphological evidence of a clay-coated charcoal fragment in the upper surface offers limited but tangible evidence that wattle-and-daub formed part of the construction of Building 2. The location might suggest a separation of the hearth/living area from another ‘room’ or storage area in the east (represented by surfaces 105/106) or may be evidence of panelling on the interior walls. The former hypothesis is perhaps more likely given that the PCA results of the lower surface, particularly PC1, indicated a western ‘edge’ to the activity area (Figs. 10, 17 and 18). Why an internal panel would be coated in clay is unclear, although this was also hypothesised at the Pictish farmstead at Lair, which returned a fragment of daub and clear evidence of animal housing and internal division (Strachan et al., 2019, p. 103; Reid et al., forthcoming). The presence of wood ash alongside the charred clay/charcoal fragments could indicate that the upper surface captured in the western end of the trench relates to the burning event observed in the north of the structure, rather than a continuation of the upper floor layer (105) as originally thought. Should this be the case, the visible extent of 105 in the field may not be a superseding floor at all, but rather turf slump and/or roof collapse associated with the burning event and subsequent degradation. It may alternatively represent a later dumping episode of unknown date.

Neither the geochemical data nor micromorphological evidence indicated that the structure extended eastwards beyond the visible limit of 105/106, which appeared to respect a concentration of postholes in the centre of the trench (Fig. 18). The geoarchaeological evidence contributed to the understanding of the plan of the structure, suggesting that it was approximately 8 m in length and 5 m in width, with a straight end wall on the southeast and a rounded northwest end. This form is similar to the heel-shaped building found at Portmahomack, a high-status early medieval settlement and monastery in northern Scotland (Carver, 2016, p. 134; Carver et al., 2016, p. 228–246). The Portmahomack structure appeared to be constructed with a turf wall and wattle cladding and was interpreted as a craft workshop that had at least two phases of the use – the first during the 8th century and the second in the 9th/10th centuries when it was converted into a grain drying kiln (Carver et al., 2016, p. 235).

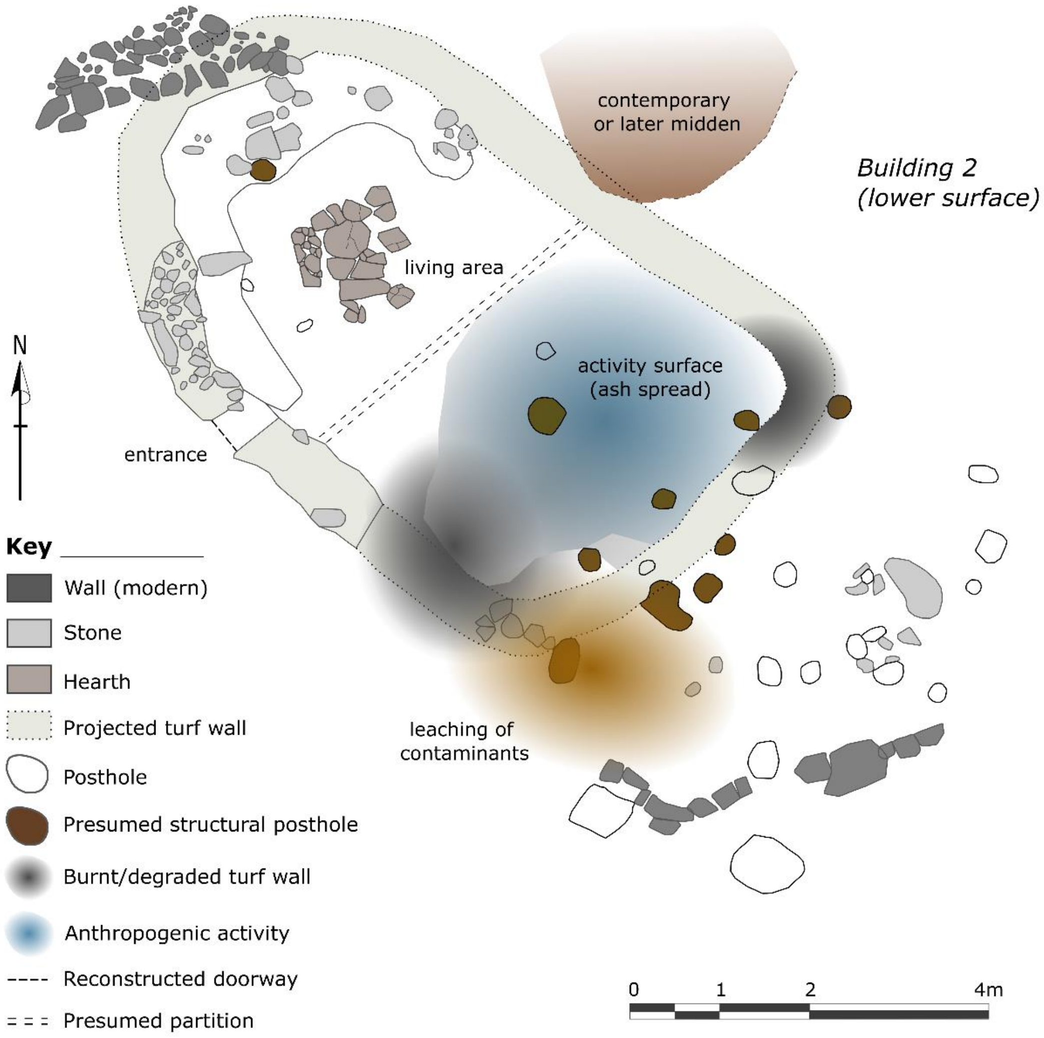

Fig. 18. Interpretive plan of Burghead lower surface, based on integrated field, microrefuse, geochemical and micromorphological evidence. For interpretation of the colour in this figure and legend, the reader is referred to the web version of this article.

There is little evidence to suggest the function or status of Burghead Building 2, other than a rotary quern stone and its location towards the seaward end of the upper citadel (a position which one may assume is of high status). Recent excavations have uncovered a concentration of workshops with bone and shell middens in the lower citadel, where the volume of material contrasts with the limited artefactual and faunal record recovered from the 2015–17 trenches. This contrast alone may suggest that Building 2 had a more domestic function, however preservation was considerably better in the lower citadel and additional post-depositional factors affecting Building 2 (truncation, stone robbing, possible reuse) are likely to have exacerbated this difference. It is also possible that upper citadel buildings were kept cleaner and/or were more thoroughly robbed of materials at the end of their life, and that this may have been related to their higher status. Indeed, a large pit with midden-like material (Fig. 18) at the northern side of the building contrasts with the above-ground middens that occur on the lower citadel.

Extensive bioturbation and illuviation meant that it was not possible to convincingly identify 105 or 106 as floor layers in thin-section, with many of the characteristic properties (microstratigraphy, planar voids, compaction, horizontal distributions) being completely absent (Milek, 2012; Rentzel et al., 2017). In this instance, recognition of them as occupation deposits was achieved primarily through the spatial geochemistry results, mirroring the findings of the comparative geoarchaeological study on the broadly contemporary Pictish building at Lair (Reid et al., forthcoming). However, micromorphology was able to clarify the composition of the Burghead layers and demonstrated the presence and survival of anthropogenic material. The overall issues identified at Burghead are therefore similar to those of urban dark earths – a term used to refer to thick, poorly stratified, dark-coloured, non-peaty deposits that contains anthropogenic material (Nicosia et al., 2017, p. 331). The homogenous appearance of dark earths means that they provide little archaeological detail at a macroscopic scale, and soil micromorphology is often successfully used to understand the type and rate of the processes involved in their formation (e.g. bioturbation, chemical weathering, agriculture, and anthropogenic dumping and mixing) (Macphail, 1994, 2014; Cremaschi & Nicosia, 2010; Devos et al., 2013a, 2013b; Borderie et al., 2015). Dark earths challenge the traditional concept of ‘one stratigraphic unit equals one action’ (Harris, 1989) and the stratigraphy at Burghead appears to represent these processes at a relatively thinner scale (Nicosia et al., 2017, p. 339). This suggests that the same methodological and theoretical principles applied to dark earths (see Macphail et al., 2003; Borderie et al., 2015; Nicosia et al., 2017) should also be applied to other poorly stratified occupation deposits.

5.2. Dunnicaer

The northeast corner of the Dunnicaer trench returned a markedly higher quantity of burnt bone than observed elsewhere across the sampled area (Fig. 19). Given its proximity to the hearth, it is most likely that the cluster resulted from the deliberate dumping of hearth waste, although the comparatively low magnetism and limited quantity of charcoal might suggest that larger bones and bone fragments were picked out and placed there, rather than being swept up together with ash and charcoal residues. More generally, there was a broad correlation between the highest concentration of elements and the highest quantity of bone and charcoal microrefuse. The most obvious suggestion is that the hearth residues were the primary contributor to geochemical signatures, however it is also possible that they acted concurrently as element traps and archives. Previous studies have demonstrated that the preservation potential of certain elements is dependent on the presence/absence of fixing agents (such as bone and charcoal) that can retain and even uptake levels of Ca, P, Sr, Zn and Cu (Wilson et al., 2006, 2008; Davidson et al., 2007). Bone distribution correlates most closely with Ca, Sr, Zn, and to some extent Cu and Mg, and would appear to provide further support for this finding.

The increased organic content identified in the southwest corner of the trench has no clear source but may be attributable to turf wall construction that has since degraded and slumped over onto the hearth rake-out, perhaps resulting in a commingled organic/magnetic signature (Fig. 19). Its proximity to the bedrock could suggest that the structure utilised the exposed geology on the eastern side of the trench as part of the wall for the structure. If so, this would provide rare evidence for construction, as definite traces of outer walling and postholes were only identified in association with one other structure on the fort (Noble et al., 2020).

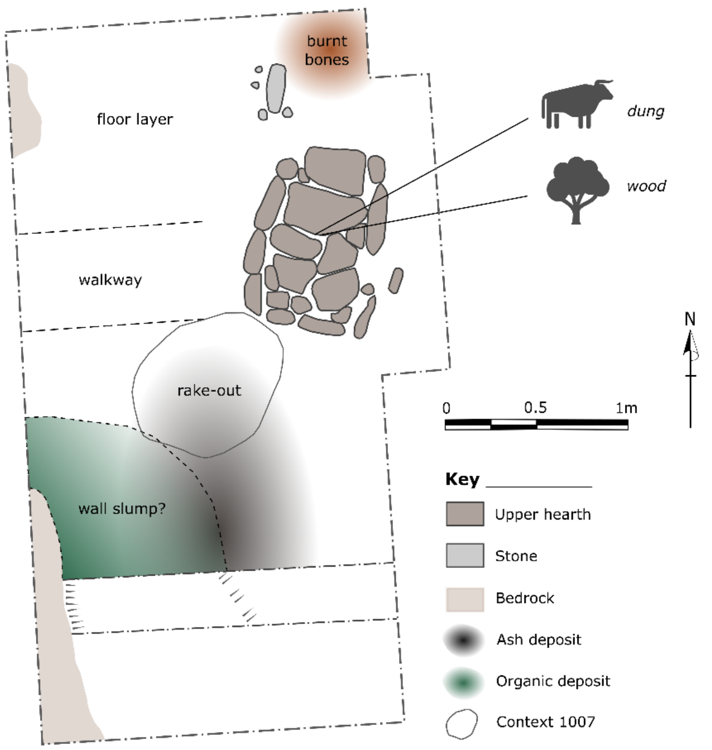

Fig. 19. Interpretive plan of Dunnicaer lower terrace structure, based on integrated field, microrefuse, geochemical and micromorphological evidence. For interpretation of the colour in this figure and legend, the reader is referred to the web version of this article.

The difference in magnetic signatures observed between the upper hearth and the area of context 1007 supports the latter's interpretation as hearth rake-out (Fig. 19; Noble et al., 2020, p. 283). It would also suggest that this extended further towards the south of the trench than was visible in the field. The elevation of P, Mn and Zn within the hearth – and P and Mn within the rake-out – suggests that dung may have supplemented the fuel source, with the geoarchaeological study at Lair identifying enrichment of these elements in the area of an early medieval longhouse believed to house animals (Reid et al., forthcoming). Magnetic signatures could also have resulted from the use of wood ash mixed with heated soil material from the base of the hearth, or soil-rich fuel sources such as turf or peat (although characteristic evidence for the latter was missing both in the field and in thin-section). Field and experimental studies have demonstrated that cattle dung is an efficient fuel when dried and capable of reaching a high enough temperature to result in an enhanced magnetic signal (Carrancho et al., 2009; Braadbaart et al., 2012). Micromorphological work at the Iron Age Clachtoll Broch has also confirmed the presence of wood, peat and dung within a single hearth, and recognised that the use of fuel types changed frequently, perhaps reflecting seasonal changes depending on availability (Roy, 2022). The presence of burnt animal bones, and the enrichment of Ca within the hearth deposits at Dunnicaer suggests that the upper hearth on the lower terrace primarily served a domestic function related to food preparation and consumption, rather than being associated with craft or metalworking. Dung generates a consistent temperature, and its fire is easy to maintain over longer periods of time, making it a particularly useful fuel source for domestic activities such as food preparation and heating dwellings (Braadbaart et al., 2012, p. 845).

The presence of charcoal-rich lenses either side of a thicker trampled layer is suggestive of a maintenance practice that involved the treatment or sealing of well-worn floor deposits with ash. Both wood ash (calcium carbonate) and faecal spherulites (present in animal dung) dissolve rapidly when exposed to rainwater, thus their absence in the free-draining soils at Dunnicaer is unsurprising (Canti, 2003; Braadbaart et al., 2017; Canti & Brochier, 2017a, 2017b; Karkanas, 2021). Interestingly, remnants of ash-spreading were more apparent in thin-section than in the spatial distribution maps, providing an interesting contrast to the findings at Burghead. This is convincing evidence that the deposit targeted for grid sampling was the floor layer 1009.2 and that the geochemical results are therefore representative of a repeatedly trampled activity surface.

The rebuilding lens (1009.4) and shallow floor deposit (1011) identified in relation to the lower hearth likely indicate the removal of cumulative layers prior to the building of the new hearth, reflecting a pattern of reuse observed more widely at Dunnicaer. Multiple rebuilding episodes in the upper terrace were evidenced by superimposed hearths, structures, and features, suggesting that structures were built, repaired, and replaced while retaining similar ground plans (Noble et al., 2020, p. 277). This has been interpreted as a response to intense activity on the site and rapid expansion of the settlement over a relatively limited area (Noble et al., 2020, p. 320). The removal of previous occupation deposits is therefore an important consideration in structures where occupation deposits are thin or fragmentary. Microlaminations containing more nuanced evidence of domestic activity are likely to have been removed, truncated, or disrupted through these cleaning events (see Milek, 2012, p. 134). Again, this challenges the concept that a single stratigraphic unit represents a single activity. Maintenance practices are part of the fabric of daily life, and it is therefore misleading to equate thin or homogenous stratigraphy with an absence of evidence for settlement activity.

5.3. Evaluation of the integrated geoarchaeological approach

The results presented above illustrate the value in conducting multi-method, integrated geoarchaeological approaches on poorly preserved and fragmented archaeological sites. At Burghead, PCA and multi-element by XRF were able to establish the soil element profile for an area of known contamination in the upper surface, allowing the 'noise' from the affected area to be effectively filtered out. This enabled the recognition of more 'authentic' patterns of enrichment but needed to be undertaken in relation to microrefuse analysis and the presence/absence of modern industrial waste. Comparison of the distribution maps and PCA results also aided the interpretation of soluble salt concentrations in the lower floor and indicated that leaching of elements (particularly Fe and S) had occurred and affected soil element concentrations in the lower surface. As this was almost exclusively restricted to the known area of contamination, it was possible to distinguish these enrichments as anomalous and not related to the archaeological use of space.

Results from Dunnicaer have indicated that element concentrations are partly related to the presence/absence of fixing agents, suggesting that certain anthropogenic signatures are more resistant and may persist in soil for relatively long periods of time in comparisons with other elements that can leach more rapidly (Wilson et al., 2008, p. 423). Variations in pH also affect chemical processes such as bioavailability and vulnerability to leaching, however the narrow range of soil pH values observed at both sites indicate that the elemental variations are largely due to other factors, such as anthropogenic deposition (Entwistle et al., 1998, p. 63–64). The interpretation of multi-element results should therefore always be made in comparison to data on the concentration of other elements and microrefuse, as well as pH which will affect the survival of different element types and fixing agents such as bone (Milek & Roberts, 2013, p. 1863).

On its own, micromorphology provided clear evidence for the post-depositional processes affecting the sites. In the better-preserved stratigraphy at Dunnicaer, micromorphology was able to detect discrete depositional events and evidence for remodelling prior to the construction of the upper hearth. Moreover, it was able to identify areas of surviving microstructure and filter out the effects of bioturbation – a feat not achievable in the field or through chemical survey. Extensive illuviation and near complete bioturbation of the archaeological stratigraphy at Burghead meant that floor layers were not readily identifiable in thin-section, however one of the block samples did capture an area of unique preservation not recognised during excavation that provided detail regarding structure construction and/or destruction. It is also very promising that surviving characteristics of the use of space were present in the geochemical, magnetic and elemental data, even when floor layers were not preserved in thin-section. This mirrors recent findings at the site of Lair, in Perthshire, where floor layers were very thin, fragmentary and had been affected by bioturbation, but revealed clear pattering in geochemistry and magnetic susceptibility (Reid et al., forthcoming). It was also hypothesised that maintenance practices and the use of floor coverings may have contributed to their limited recovery (Reid et al., forthcoming). Indeed, Building 1 at Burghead (Fig. 3) appears to contain evidence for a suspended wooden floor. The results of these studies have therefore demonstrated the value in conducting geoarchaeological investigation on fragmented or poorly preserved buildings but also the need for integrated approaches, rather than a reliance on individual techniques

6. Conclusion

The integrated geoarchaeological methodologies presented in this study have proved fundamental to the assessment of preservation, site activities and post-depositional events at two fragmented structures in northeast Scotland. They have helped clarify the outline and dimensions of a poorly preserved building at Burghead, and provided new layers of detail, including wattle-and-daub construction, partitioning of space, interior remodelling, and the use of dung as a potential fuel source that have enriched our understanding of daily life in first millennium AD coastal settlements. The indication that both buildings served a domestic function supports field interpretations and enables the reconstruction of site organisation, particularly in the larger fort at Burghead where ongoing excavations are uncovering workshops and middens situated away from these structures. The use of overlapping microrefuse and geochemical datasets, correlation tables, and principal component analysis greatly enhanced the interpretational power of individual techniques and were key to recognising the impacts of post-medieval contamination and biases in the survival of different element types. Integrating these bulk soil analyses with soil micromorphological analysis then enabled the recognition of floor layers and maintenance practices, providing key detail about the survival, composition, and compaction of the identified occupation deposits.

Combined, this study has demonstrated that geoarchaeology can play a significant role in elucidating the original composition and spatial patterning of highly fragmented buildings and occupation surfaces. Evidence survives in the micro-residues deposited by human activity and can be meaningfully linked to the practices that governed everyday life. This study has also shown the need to consider the post-depositional processes that can affect their integrity at the macroscale, and highlights the pitfalls associated with equating thin or homogenous stratigraphy with an absence of evidence for settlement activity. Doing so will not only omit crucial information but also risks the creation of less reliable interpretations of archaeological structures and their assemblages. Though this study has presented the results from early medieval sites in Scotland, it offers an integrated methodology and theoretical principle that can be applied to fragmented buildings and occupation deposits around the world.

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Author Contributions

Vanessa Reid: Conceptualisation, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review and editing, Visualisation
Karen Milek: Conceptualisation, Methodology, Writing – review and editing, Supervision, Funding acquisition
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Competing Interests

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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8. Research-led Guidelines

Geoarchaeology: A Short Guide

Vanessa Reid in partnership with Lisa Brown, Kevin Grant, Kirsty Owen and Karen Milek

This output was developed as part of a six-month CASE placement with Historic Environment Scotland (HES) that was integrated within the IAPETUS PhD studentship. It comprises research-led information and practical guidelines on the application of geoarchaeological methods and principles, and is supported by short case studies demonstrating the variety and scope of geoarchaeological research within Scotland. These guidelines have been specifically aimed at a non-specialist audience in an attempt to counteract the perception of geoarchaeology as a wholly specialist discipline, encourage wider engagement with its techniques, improve the quality and collection of data, and place this agency within the hands of the excavators and research directors (RQ *ix*; Chapter 1, section 1.3). The intended users of the guidelines include community groups, commercial archaeology units and consultants, and those involved in academic research projects. This document may also be used by local authority archaeologists to advise on the development of planning strategies and to disseminate best practice.

The concept of this output was developed by Lisa Brown and Karen Milek, and the nature of the document (practical guidelines) was a collaborative decision made by all authors. As the primary author of this output, I was responsible for the production, formatting, research and visualisation. I wrote the first full draft of the guidelines and corrected subsequent drafts based on comments by the co-authors. Lisa Brown has been the primary liaison with HES throughout this partnership and has provided images for the publication on their behalf. Karen Milek has also provided her own images for use under copyright. This document comprises the most recent version of the guidelines and whilst its written content and order are unlikely to change, formatting and images are subject to change during publication. At the time of writing the guidelines, the Soil Analysis Support System for Archaeologists (SASSA) was active and has been referred to throughout. The webpages are currently inaccessible however it is hoped that they are revived prior to publication.

HISTORIC ENVIRONMENT SCOTLAND | ÀRAINNEACHD EACHDRAIDHEIL ALBA

GEOARCHAEOLOGY

A SHORT GUIDE

VANESSA REID

In partnership with Lisa Brown, Kevin Grant, Kirsty Owen and Karen Milek

Contents

Front image: Newly manufactured thin-section slide from early medieval structure at Lair, Glenshee (Case Study 4). Photograph © Vanessa Reid.

Introduction

Geoarchaeology involves the investigation of archaeological soils and sediments using a wide range of desk, field and lab-based techniques. When material is removed from an archaeological site, it is typically discarded as waste or reinstated after excavations have concluded. However, these deposits often contain a wealth of information that can help reconstruct the history of a site.

The goal of geoarchaeology is to understand how sites formed and how they have been modified over time. This information is contained in the physical, chemical and biological properties of archaeological deposits. By examining these properties, geoarchaeology helps us to interpret the natural and human events that have resulted in these signatures. It also provides important contextual information about the preservation environment, which can inform management strategies and ground our interpretations. Ultimately, geoarchaeology allows us to tell more meaningful stories about the past.

Geoarchaeology helps us to understand the archaeological record a variety of different scales. At the feature or structure scale, it can reveal how deposits were formed and what a feature might represent. At the site level, it can provide information about preservation conditions, occupation patterns and the location of activity areas. At a landscape level, it can identify where sites are located, reconstruct past environments and land-use practices, and provide insights into the environmental impact of human activities. There is also huge potential for geoarchaeology to help us understand how climate change is impacting the archaeological record.

Scotland has produced a diverse range of geoarchaeological studies and much of the research has been world-leading. Investigations have occurred at all scales mentioned above and a significant body of work based in Scotland has focused on the development and testing of emerging geoarchaeological techniques. However, these approaches have only seen limited uptake in community projects or commercial briefs and there is a significant opportunity to increase the depth and quality of archaeological research through geoarchaeological enquiry.

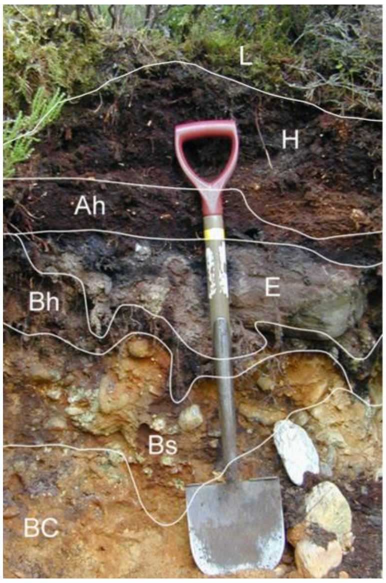
This Short Guide provides advice on how geoarchaeological techniques can be applied to archaeological investigations. It begins with an overview of the major events that impact archaeological sites and explores how geoarchaeological methods can help us understand these. The guide also provides practical advice on geoarchaeological techniques, including how to describe soils and sediments in the field, how to recognise the factors that have affected site formation, how to correctly take samples, and how to select the most appropriate laboratory-based analyses (which may not always be needed).

This guide is aimed at anyone wishing to get a broader understanding of geoarchaeological approaches and how to integrate them into archaeological practice. This includes community groups undertaking desk-based assessments or fieldwork investigations, commercial archaeology units and consultants, or those involved in academic research projects. This document may also be used by local authority archaeologists to advise on the development of planning strategies and to disseminate best practice.

Soils vs Sediments

Fundamental to all archaeological fieldwork, and underlying all geoarchaeological sampling strategies, is an understanding of the differences between soils and sediments.

Soils develop in place and are a mixture of weathered rock and decaying organic material. They require time and a stable ground surface to develop and are influenced by their underlying geology, climate and living organisms. For example, soils formed on granite and highly organic peats tend to be very acidic, whilst soils formed on chalky limestone tend to be pH neutral or alkaline. Soil development results in layers (soil horizons), which together form a soil profile (Fig. 1). Humans can alter soil profiles by cultivating land and physically disrupt them by digging. However, most of the soil-forming work is a complex interplay of physical, chemical and biological activity. A more detailed summary of Scotland's soil formation can be found here.



Iron Humus Podzol

L plant litter

H accumulation of organic matter (humus)

Ah humic topsoil

E leached mineral horizon

Bh accumulation of leached organic material

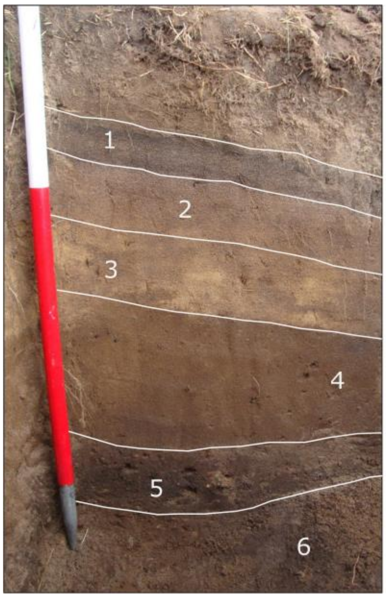
Bs leached iron and aluminium

BC transitional layer between B and weathered parent material (C horizon)

Fig. 1. *Example of soil profile commonly found in Scotland (photograph © James Hutton Institute)*

Buried soils – which have been buried under a later deposit of material (either natural or human-made) – are of particular interest to archaeologists. As they developed during periods of landscape stability, they represent former ground surfaces for human occupation and are a good source of environmental evidence. They also provide the basis for agricultural regimens and often contain key information about land management practices such as tillage and manuring. Soils can be buried under natural deposits, such as wind-blown sand, or beneath structures like walls, banks, monuments, middens, or agricultural ridges and terraces. Burial effectively stops further soil development and preserves the profile as a record of past soil conditions.

Sediments, on the other hand, are layers or collections of particles that have been moved from their original source and deposited elsewhere by natural or human activity. The most common natural sediments on archaeological sites are flood deposits (alluvium), wind-blown deposits (aeolian sediment), and material that has eroded and moved downslope (colluvium). As humans are constantly digging, moving, demolishing, cleaning and discarding material, so-called anthropogenic (human-made) sediments often make up the majority of sedimentary materials on archaeological sites. Sediments can also play an important role in the burial and preservation of sites (Fig. 2).



Sediment Profile

1 buried horizons (black from humic material)

2 buried sandy plough layer

3 yellow wind-blown sand cut by plough marks

4 buried clayey plough layer

5 buried B horizon

6 glacial till

Fig. 2. *Example of buried sediment profile in rig-and-furrow at Sands of Forvie, Aberdeenshire (Canmore 20844; photograph © Karen Milek)*

> **In short…**
>
> Soils develop in the absence of movement, whilst sediments are the result of movement.

Site Formation and Modification

No archaeological site is found in the same condition as when it was first occupied. Before occupation and over time, numerous events affect the integrity of sites and artefacts, resulting in complex (and often confusing) remains. These events are known as 'site formation processes' and can affect sites by adding, removing, relocating, altering or preserving archaeological material. Being able to identify and understand these impacts is the key to interpreting sites.

This section examines the major human and natural formation processes that have operated in Scotland over the last 12,000 years. The processes covered here are intended to provide a brief overview and are by no means exhaustive. This section also looks at the major environmental conditions that affect preservation and provides a summary of the conditions in which certain artefact groups are expected to survive.

Sedimentary processes

Events that affect landscape formation are integral to the survival, degradation and discovery of Scotland's archaeology. They can deposit new sediments on a site, resulting in the burial and preservation of remains, but can also erode, redistribute and expose existing material. There is also evidence to suggest that people in the past understood the underlying geology of places and made choices of where to farm or settle accordingly. An area's geological setting can therefore offer clues into human activity before a spade has even touched the ground.

There are three main types of sedimentary process that affect Scottish archaeological sites – slope, water and wind. Each of these processes can occur at different rates and magnitudes but all involve the erosion, transportation and deposition of material.

Slope – Slope processes involve the gravitational movement of material downslope. This can be as dramatic as a landslide or a gradual creep over time. Slope deposits ('colluvium') are found at the base of slopes and can bury archaeological sites and preserve past landscapes if they occur on a large enough scale. Agriculture and deforestation are key instigators of slope processes, and so slope deposits can also act as records of human activities and their impacts on the landscape.

Water – Water processes involve the suspension and deposition of material in water. This can occur when ground surfaces become saturated, or in moving water systems such as shorelines, rivers and streams. River valleys are some of the most densely populated archaeological landscapes, and their deposits ('alluvium') can contain key information about past human settlement. Material can also be deposited in bodies of standing water, such as ponds, which may have been attractive hubs of human activity – for example, hunting or votive deposition. Water-lain deposits can remain waterlogged, resulting in good conditions for the preservation of organic material and environmental evidence.

Wind – Wind processes involve the movement of material by air. Wind uplifts small, light particles and artefacts (usually sand or silt sized) and so locations with a high sand content – coastal sites, dune systems and machair sands – are predominately affected. Rapid burial by wind-blown sands, particularly shell sands, has resulted in the exceptional survival of some of Scotland's most iconic archaeological sites (Fig. 3). The unstable and fragile nature of coastal locations means that wind erosion has also played a key role in the exposure and identification of sites that have previously been buried by sand.

Fig. 3. *Skara Brae on Orkney was buried by wind-blown alkaline shell sand which resulted in the remarkable preservation of Neolithic stone house (Canmore 1663; photograph © Historic Environment Scotland)*

Worth considering…

Slope, water and wind deposits are commonly encountered on archaeological sites but can be recorded as 'sterile' or mislabelled as 'natural' if they lack artefacts or charcoal. Because of this, it is often assumed that such deposits are of little interest to the excavator. However, these features may have been induced by human action or represent landscape-changing events that shaped the way people viewed and interacted with their environment. They could also represent periods of abandonment, and additional archaeology may lurk beneath. It is therefore important that these sediments be treated with the same attention given to more obvious human-made deposits, such as floors, middens or structures. A guide to Identifying Sedimentary Processes in the Field is provided later in this document.

Coastal processes

In addition to the processes mentioned above, there are also cases where sedimentary activity combines. Coastal erosion is of particular concern to Scotland's archaeology and is the product of cumulative wind and wave action. This results in shoreline retreat, cliff collapse and dune migration that exposes and destroys archaeological sites (Fig. 4). These natural processes occur even under normal weather conditions but are exacerbated by extreme weather events such as storms. Climate change projections predict an increase in the frequency and magnitude of these events and thus threatens our coastal heritage. SCAPE is a charity who work with the public to define and manage the archaeology, history and past environments of the coastal zone of Scotland.

Fig. 4. *Extensive coastal erosion at Dunnicaer Pictish fort, Aberdeenshire (Canmore 37001; photograph © Noble et al. 2020)*

Biological processes

Plant and animal activity can affect archaeological sites in a variety of ways. Some processes, such as the deposition of organic matter through leaf fall or animal waste, favour the accumulation of organic sediments and development of soils. Others involve the disturbance of site stratigraphy and the decomposition or redistribution of artefacts.

Archaeological stratigraphy can be extensively reworked – even completely destroyed – by plant roots, earthworms and burrowing animals (Fig. 5). This is commonly referred to as 'bioturbation'. Impacts vary depending on an animal's size and population density but typically involve the mixing of sediments, blurring of feature boundaries, and the movement of material through a soil profile. The upstanding remains of earthen monuments and turf-built structures are particularly attractive habitats for tunnelling mammals such as moles, rabbits and badgers, leaving these sites vulnerable to scarring and undermining.

Fig. 5. *Rabbit burrows at Kildonan School Shieling, South Uist (Canmore 9840; photograph © Karen Milek)*

Understanding the degree to which bioturbation has impacted a site is particularly important when sampling for radiocarbon dating. Charcoal and other material that has been moved through a profile (or introduced from nearby archaeological remains) is described as 'intrusive'. Using this material for radiocarbon dating is not recommended because the dates produced may not reflect the actual age of the feature or site and can lead to misinterpretation. While large burrows are usually obvious, evidence of bioturbation from worms and insects is not always visible to the naked eye, so microscopic analysis may be needed to assess impacts. Livestock trampling also contributes to the vertical and horizontal displacement of cultural material, as well as the fragmentation of artefacts and the compaction of soils.

Decomposition is a natural biological process that involves the breakdown of organic matter by animals, insects, fungi and other microorganisms. Organic artefacts, floors and plant material are all susceptible to this process and are rarely recovered from Scottish archaeological sites. The exception is waterlogged environments (such as peat bogs), where oxygen levels are much lower and the activity of bacteria, fungi and soil fauna is restricted. Scotland has the majority of the peat in the UK and some of the country's most iconic artefacts have been found in these contexts. However, waterlogged sites are highly vulnerable to change and any drainage can rapidly increase biological activity and acidification, resulting in accelerated decomposition.

Human processes

There are numerous mechanisms through which humans introduce material to a site. Construction, animal keeping, resource gathering for food, fuel and crafts, and the movement of particles underfoot all contribute to an occupation signature. Once deposited, these materials are then subject to further processes (such as cleaning and reuse) which affect their integrity and location.

Human processes can also affect sites long after occupation has ceased. Planned abandonment of a structure often forces a change in normal cleaning practices – for example, the removal of artefacts and deposits, the accumulation of refuse or the creation of specialised refuse areas. Objects may also be placed in meaningful ways or in significant locations. When return is not anticipated, abandoned structures may change function or be deliberately destroyed as part of cultural or individual practices. When a building collapses, the exposure of floor surfaces accelerates biological processes and increases acidic conditions. It also introduces roof material to floor surfaces, potentially obscuring any obvious stratigraphy and resulting in mixed floor-roof assemblages which can skew archaeological interpretations.

Both modern and ancient agricultural practices are known to significantly impact archaeological sites. Irrigation, manuring and clearance burning all alter the structural and chemical properties of soils and can increase their susceptibility to earthworm activity. Field clearance results in the physical removal of upstanding structures, whilst plough scars can truncate buried archaeology and redistribute large quantities of material. Artefacts that have been moved into the ploughsoil are often abraded and fragmented and suffer accelerated degradation (Fig. 6). Agriculture and deforestation can also increase the susceptibility of sites to erosional processes, such as slope failure and wind or water erosion.

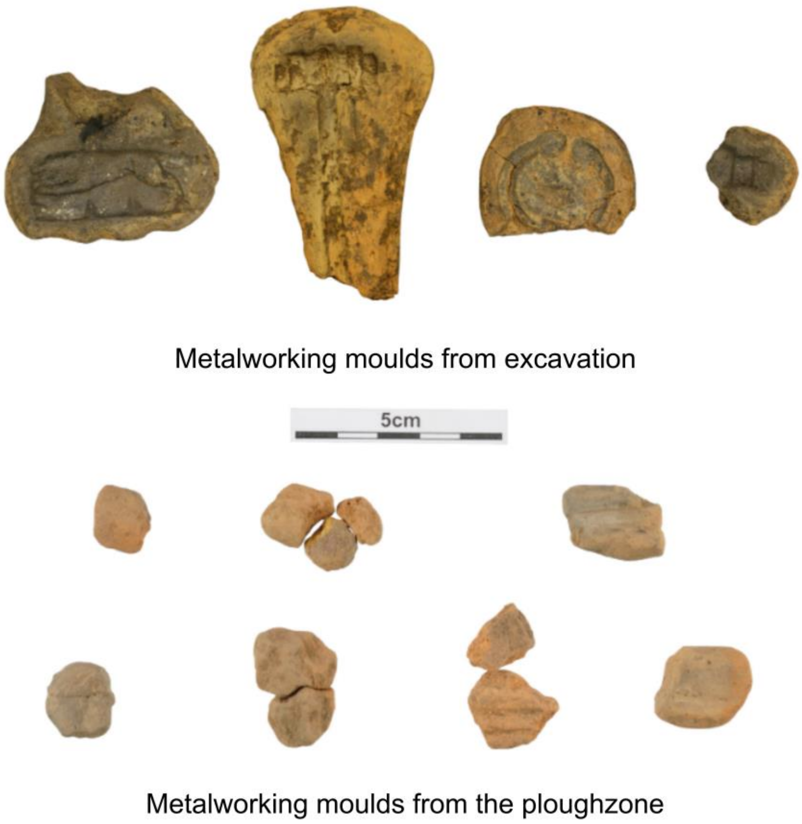


Fig. 6. *Artefact degradation in the ploughsoil at the royal Pictish settlement site at Rhynie, Aberdeenshire (Canmore 281408; photograph © Gordon Noble)*

Preservation conditions

There are many additional factors within the burial environment that determine why some types of material are recovered from archaeological sites and others are not.

The acidic soils common to Scotland promote the degradation of bone, and conditions for good preservation are rare. Well-preserved bones assemblages are predominately found in the less acidic coastal sands of the Western and Northern Isles, in river sands and gravels, or in limestone caves. The recovery of wood, uncharred plant remains, soft tissues and other non-skeletal material (fur, horns and hides) is even rarer, as these typically only survive in waterlogged (Fig. 7) or well-sealed, clayey environments where the absence of oxygen has inhibited bacterial decay.

Fig. 7. *Waterlogged preservation of branch-wood bundles providing the foundation of flooring at the Iron Age settlement at Black Loch of Myrton, Dumfries and Galloway (Canmore 62815; photograph © AOC Archaeology)*

Inorganic materials are also subject to changes following deposition. Nearly all metals will experience corrosion during burial. Corrosion products range in colour depending on the metal and soil conditions and can form as thin layers or thick disfiguring crusts. Stone artefacts and features will survive in almost all burial conditions but may undergo some physical degradation through transportation or trampling. Certain chemical processes (such as leaching) can also alter archaeological soils and stratigraphy, resulting in colour changes and the creation of additional layers. It is therefore very important that we gain a sound understanding of the burial environment before developing archaeological interpretations.

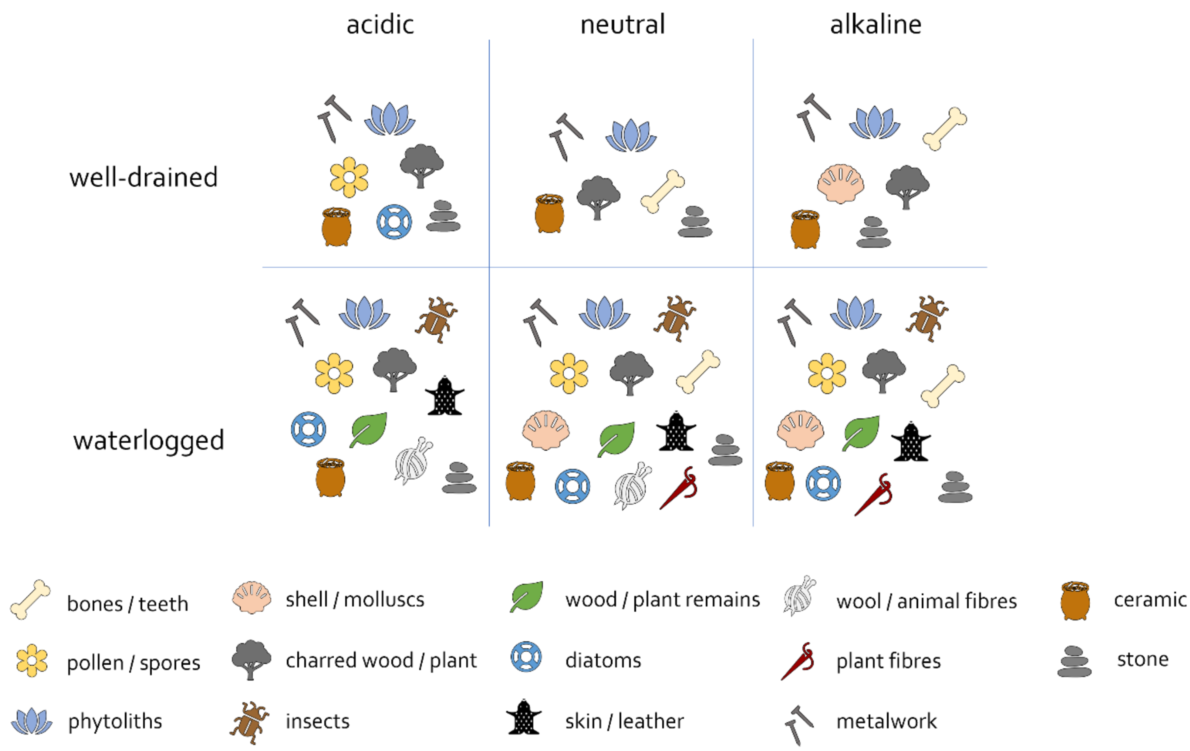


Fig. 8. *Categories of environmental and cultural material expected to survive under different preservation conditions (degree of preservation or metal corrosion may vary) (adapted from Retallack 1984; image © Vanessa Reid)*

Geoarchaeological Approaches

Each geoarchaeological method is designed to help answer specific questions. Before planning an archaeological investigation it is important to consider what questions you want to ask of a site. For example, what landscape processes have impacted a site? How was lived space organised? How have preservation conditions influenced artefact recovery? What are the current and future risks to site survival? Understanding the questions you want to address allows for the creation of appropriate sampling strategies, which are key to maximising the cost/return ratio.

Whilst individual techniques offer their own information, interpretations are greatly improved when results are combined and viewed as a whole. Many of the chemical, physical and biological properties of archaeological soils and sediments are linked and understanding these together develops more robust interpretations of the archaeological record. Many of the case studies below demonstrate this integrated approach.

As with any archaeological investigation, it is important to consider the type of work in advance and the information that you may encounter. If you are undertaking excavation or sampling it is strongly recommended that you consult a geoarchaeologist or environmental specialist at the beginning of a project. They can provide guidance on how/where to collect appropriate samples and select the most suitable methods of investigation. A Summary Guide has been provided at the end of this section.

Desk-based Assessments

Desk-based assessments are often the first step in understanding site histories and can provide information on land formation, geology and soil chemistry. There are a multitude of freely available resources that have been designed for public use and are relevant to geoarchaeological investigation in Scotland. Using these resources can help to predict preservation conditions before excavations have begun or provide contextual information when funds for further analyses are unavailable.

Almost all the maps, aerial imagery and resources mentioned below can be layered in the 'Scotland's environment' web map. This is an excellent resource for overlaying datasets and quickly gathering information for a specific area. Current standards and guidance on desk-based assessment are provided by the Chartered Institute for Archaeologists (CIfA).

> **Advice Note**
> Users should be aware that the resources mentioned below only provide an indication of soil conditions at the site level and are not a direct replacement for analysis of archaeological soil samples.

Soil and sediment data

Interactive maps provide an excellent starting point for the investigation of archaeological deposits. Resources such as the UK Soil Observatory, mySoil app and SoilFinder Scotland can be used to ascertain the soil types in specific areas, get information on soil characteristics (such as pH, texture, depth, organic matter content and temperature), and understand the differences between cultivated and non-cultivated soils. Datasets for specific soil properties, and risk maps for soil erosion and compaction, are also available from the James Hutton Institute. Additional soil apps and resources can be found here.

The British Geological Survey's (BGS) Geology Viewer and iGeology app are a set of resources which map the distribution of superficial deposits (sediments) and bedrock across the UK. They can be used in tandem with the soil resources above to provide contextual information for the physical and chemical characteristics of archaeological soils. BGS Borehole Scans (available as a mode on the Geology Viewer) is an additional archive containing a vast collection of scanned borehole, shaft and well records. Boreholes range from one to hundreds of metres deep and their records are a written description of the material that comes out of the ground. This includes information on soil conditions, structure, geology and the depth and thickness of deposits. These records are a complementary tool to the soil and geology viewers and provide more detailed information at a local scale. However, borehole record distribution across Scotland can be patchy (often focused on towns) and information may not be available for all areas.

Aerial imagery and remote sensing data

Aerial imagery and remote sensing data provide information on topography and modern land-use and are often used to identify cropmarks. The use of satellite imagery is now routine, with the most common resources being Google Maps and Google Earth. LiDAR data – which produces 3D models and maps of the environment – is available through the Scottish Remote Sensing Portal. The benefit of LiDAR data is that it can be processed to remove the tree canopy, revealing more information in the ground surface beneath (Fig. 9). Historical aerial photographs are housed in the National Collection of Aerial Photography and can be used to identify past land use practices which may have affected site survival.

Fig. 9. *LiDAR image of Tap O' Noth hillfort in Aberdeenshire showing dense hut platform settlement. LiDAR image from a survey funded by Forestry & Land Scotland, Aberdeenshire Council Archaeology Service and University of Aberdeen (Canmore 17169; image © James O'Driscoll 2020)*

Dynamic Coast is an additional online platform more specifically related to coastal change. It incorporates the results of aerial photography, satellite imagery and LiDAR data to provide interactive mapping of shoreline changes that have occurred over the last 130 years. It also provides predictions of future change. This can help users reconstruct past coastal landscapes or recognise current and future risks of erosion.

Case Study 1: Modelling a Coastal Wetland

Coastal wetlands offer a unique opportunity to study how the archaeology of prehistoric maritime communities was shaped by dynamic changes in sea-level. Much of our understanding has come from Quaternary geological research, however scales of analysis are often too broad for detailed archaeological interpretations to be drawn out. This has resulted in a problematic gap in archaeological narratives.

Desk-based research on Loch Spynie – a former lagoon system on the Moray Firth – has presented a new a method for refining these palaeogeographic models. Freely available data (including LiDAR, BGS borehole scans and layers from the Geology of Britain Viewer) were used to identify indicators of past sea-level and geomorphological features such as raised beach ridges, lake deposits, and marine, bog and estuarine sediments. This was combined with archaeological sites from historic maps and the Canmore database, in order to understand settlement activity over time and constrain past shorelines.

The approach identified that Loch Spynie would likely have been a Late Neolithic/Early Bronze Age maritime haven, capable of facilitating both local and long-distance journeys by boat. It also showed that the maritime movement of people, material and ideas in this region was set within a landscape of dynamic coastal change.

Read more about this case study:

- Research article

Field-based Techniques

Fieldwork is the backbone of geoarchaeological research. It influences the choice of lab analyses and can confirm or disprove the findings of desk-based assessments. Detailed descriptions of soil or sediment profiles are the single most cost-effective way to understand site formation processes, as they require little to no additional equipment. Other methods focus on the collection of data in the field, which can be recorded manually or uploaded onto a computer for later analysis. Current standards and guidance for archaeological excavation are provided by the Chartered Institute for Archaeologists (CIfA).

Test-pitting and soil augering

Field-based geoarchaeological analysis first begins with the identification of archaeological stratigraphy. Test-pitting and soil augering (coring) are commonly used for site prospection and are particularly useful in areas with deep sediment sequences, where they can locate anthropogenic deposits and buried ground surfaces. The number and spacing of sampling points will depend on the questions asked, the scale of the landscape, and the size and frequency of the features you are hoping to find. Equipment required ranges from a simple spade to sophisticated hydraulic systems, and certain soil conditions will be more suited to specific auger types. A useful summary can be found here. Both test-pitting and soil augering provide sequences for soil descriptions and samples can also be used in subsequent laboratory analyses.

Fig. 10. *Hand auger used for soil and sediment descriptions in the field (photograph © Lorne Gill/SNH)*

Case Study 2: Climate Change at Caerlaverock

Caerlaverock Castle (Canmore 66100) is a 13th century moated castle located on the coast of the Solway Firth. Construction of the original building (Canmore 66101) took place around 1229, however it was abandoned after a period of just 50 years and a new one built higher up the hill. Research by the University of Stirling found that the first castle had fallen victim to climate change, when huge coastal storms hit the Solway coast in the medieval period.

Geoarchaeological work at the site has focused on understanding the nature and timing of the climate change events, and the effects they wrought on archaeological features that led to the abandonment of the old castle. Cores and samples extracted for sediment descriptions revealed that mud from storm surges had penetrated beyond the castle, and the moat, earthworks, and surrounding ditches had suddenly filled with silt and clay. Complementary diatom analysis showed that this sudden surge of sediment was marine in origin, coming inland from the coast and probably through a harbour. LiDAR imagery also revealed a series of large gravel ridges, 200 m long and 20 m wide, that formed when huge storms repeatedly hit the coast. When the storms ceased, the old castle lay some 200 m further away from the coast.

More recent investigation has involved a programme of coring to identify dateable sediment in an area of the site believed to be a harbour. Standard archaeological excavation could not achieve this, as there were three metres of sand lying above bedrock. The sediments from this area only reflected still water and low-energy deposition, suggesting that the entrance was blocked off by people increasingly scared of the changing climate. This indicated that storm surges skirted round the ‘harbour’, pushing over low cliffs and across parkland to pour into the moat surrounding the old castle.

Read more about this case study:

- Blog entry
- Research article

Fig. 11. *Wrapping core samples from Caerlaverock Castle (Case Study 2) for sediment descriptions, optically stimulated luminescence (OSL) and infra-red stimulated luminescence (IRSL) dating (Canmore 66101; photograph © Historic Environment Scotland 2021)*

Soil and sediment descriptions

Soil and sediment descriptions are something almost all archaeologists will have encountered in the field. Taking notes on a deposit's composition, colour and inclusions are routine, however descriptions that lack detail or use ambiguous terms (such as 'chocolatey') can affect the understanding and interpretation of site stratigraphy – particularly in post-excavation stages. Having a more standardised approach to soil description allows for the comparison of deposits and is particularly important if samples are sent for laboratory analysis. Including a little bit of additional detail can also help to identify the processes involved in forming and preserving a site, as well as any modifications that have occurred since its burial.

Field archaeologists are often best placed to carry out these descriptions, as they tend to have a more intimate understanding of the deposits than specialists who may only make periodic visits to site. With just a few adjustments, field descriptions of archaeological contexts can easily be upgraded to geoarchaeological assessments. Practical Advice on what to include (and why) has been provided later in this document.

Phosphate analysis

Phosphate analysis is usually conducted in a laboratory but can be achieved in the field if a quick assessment is needed to inform sampling strategies. Phosphorus is introduced to settlement areas through human and animal tissues and excrement, so field applications usually involve the identification of areas with high levels of this material. This includes rubbish pits and middens, animal pens and houses, areas of manuring, latrines, and potential grave sites where a body has completely decomposed and bones are not preserved.

Larger scale phosphate surveys are also used to identify the limits of a site. These are usually conducted on a grid system or radial survey and involve taking a number of samples and comparing phosphate concentrations (see Choosing a Sampling Strategy). The cheap and quick methods of phosphate analysis provided below (Table 1) can be used for these larger surveys, however additional post-excavation analysis (laboratory phosphate or multi-element analysis) may be needed to confirm the results and allow for statistical analysis.

Table 1: Common field methods for phosphate analysis

	Spot Test	**Reflectometry**	**Melich-2 and Colorimetry**
Data type	Qualitative	Quantitative	Quantitative
Sample prep	No sample prep	Air-dry and sieve 2mm	Air-dry and sieve 2mm
Ease of use	Very simple	Simple	Relatively simple
Requirements	Pre-made chemical solutions; filter paper; deionised water	Reflectometer with accompanying reagents and test kits	Mehlich-2 soil extractant solution; colorimeter and associated reagent
Methods	SASSA Qualitative Phosphate Technique	Follow manufacturer instructions	Follow manufacturer instructions

Practical Advice

Understanding whether a feature is relatively high or low in phosphates requires a range of samples for comparison. These can be taken from different areas or features in a site, or from another deposit in a sampled section. It is also useful to take reference samples from off-site areas to account for background levels (see Control Samples). When used as a survey method, phosphate results should ideally be combined with other approaches such as fieldwalking, geophysics or aerial imagery.

Magnetic susceptibility

Magnetic susceptibility determines the degree to which a soil or sediment is magnetic. The magnetic characteristics of a soil or sediment can be influenced by natural factors such as soil development processes but the effects of human activities are much more profound. Soils and sediments that have been affected by high temperatures (e.g. burning), or which contain minute fragments of iron hammerscale, will show distinct differences that can be compared across a profile or mapped across a site.

For most archaeological investigations, magnetic susceptibility analysis is conducted using a portable, lightweight meter (such as the Bartington MS3 meter) and an accompanying sensor. Some sensors, such as the Bartington MS2B Dual Frequency Sensor, allow users to carry out measurements at two different frequencies. Comparing values across both frequencies can help identify the presence of the ultrafine magnetic particles created by microbial activity. This type of sensor requires samples to be air-dried, sieved and weighed, and so the analysis is most often conducted in a laboratory.

There are also a wide range of sensors available for use in the field that remove the need for additional sampling, drying and sieving stages. Each sensor has a unique application and produces readings at different depths of penetration. A summary is provided below (Table 2).

	MS2D Surface Scanning Probe	MS2F Surface Point Probe	MS2H Downhole Sensor
	Table 2: Common Bartington equipment for field analysis of magnetic susceptibility		
Approach	Rapid assessment of the top 100mm of the land surface	Stratigraphic study of exposed geological and archaeological sections	Sub-surface measurement in 25mm diameter auger holes
Applications	▪ Site prospection ▪ Assessment of slope processes	▪ Identification of buried soils and horizons with burning/burning residues ▪ Stratigraphic correlation ▪ Useful if uneven surface conditions prevent good contact with the MS2D probe	▪ Characterisation of cultural stratigraphy ▪ Identification of buried soils ▪ Assessment of soil development and/or erosion ▪ Stratigraphic correlation across a site
Sampling surface	Ground surface (litter/vegetation should be removed if possible)	Exposed section (cut-back and cleaned)	Auger holes (22-25mm diameter)
Requirements	Probe is operated in conjunction with the MS2 Probe Handle, the MS meter, and a laptop computer running the meter's software.	Probe is operated in conjunction with the MS2 Probe Handle, the MS meter, and a laptop computer running the meter's software.	Requires a tube to give an assembled length of 1m. Further extension tubes can be added to increase probe length. Probe is operated in conjunction with the MS meter, and a laptop computer running the meter's software.

Case Study 3: Spatial Patterning of House Floor Debris

Cille Pheadair (Canmore 139161) is a Norse-period farmstead on the island of South Uist in the Outer Hebrides. Excavation was undertaken as a rescue project before the site was destroyed by coastal erosion and revealed nine phases of occupation with five longhouses and many smaller buildings. House 700 (constructed cal. AD 1030–1095) was the first stone longhouse to be built on the site but was shortly replaced by House 500 (constructed cal. AD 1060–1100), resulting in the truncation of earlier floor deposits. House 500 was the larger of the two houses, with a long main room leading to a small square room, both of which contained hearths.

Phosphorus and magnetic susceptibility were included as part of a detailed investigation that examined the spatial mapping of various ecofacts and artefacts across both house floors. Spatial patterns of debris material were broadly similar, however values of total phosphorus were much higher in House 500. This indicated that House 500 had a greater longevity and intensity of use than the earlier structure. The highest phosphorus concentrations were recorded within the hearths, where they coincided with distributions of burnt and unburnt animal bone and elevations in magnetic susceptibility. It was concluded that these signatures likely reflected accumulated food and fuel waste produced during cooking activities.

Elevations in magnetic susceptibility were also recorded along the east wall of the main room in House 500 (Fig. 12). Here, the elevated values indicated that re-deposited peat ash had been laid down to form a floor surface. The approach of comparing spatially mapped chemical data with debris distribution patterns shed light on the activities within House 500 and helped to clarify the truncated patterning within House 700.

Read more about this case study:

- Cille Pheadair: a Norse Farmstead and Pictish Burial Cairn in South Uist

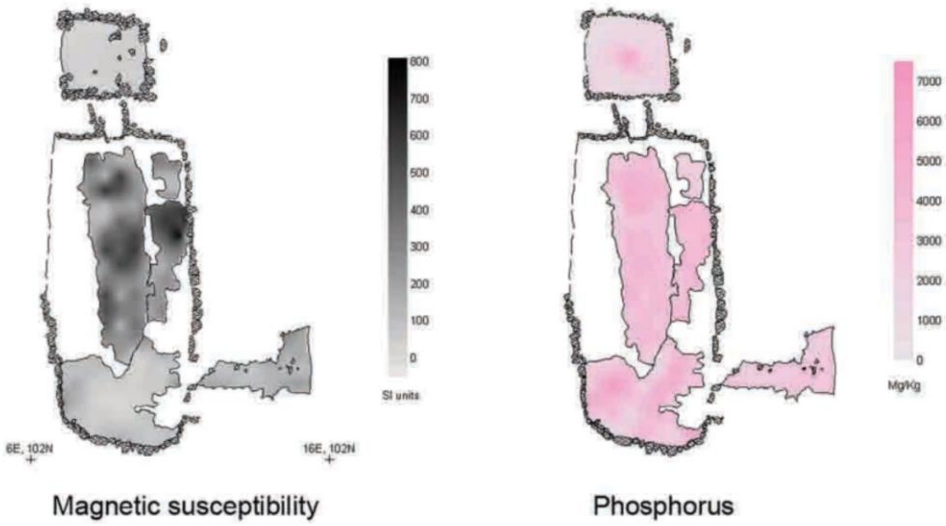


Fig. 12. *Distribution levels of magnetic susceptibility and phosphorus in House 500, Cille Pheadair (Case Study 3) (Canmore 139161; image © Parker Pearson et al. 2018)*

Practical Advice

If conducting magnetic susceptibility with a laboratory sensor (e.g. MS2B Dual Frequency), analysis should be conducted on samples that are air-dried and sieved to 2 mm. However, samples from waterlogged deposits may contain a significant quantity of unstable iron minerals which could be affected by oxidation during the air-drying process. If dealing with such deposits, measurements should be made immediately on the wet samples followed by air-drying to determine the dry mass of the sample.

Standard Lab Techniques

Laboratory techniques complement the interpretations made on site and can be used to provide better quantified data and to answer specific questions about site formation processes. This set of techniques need to be carried out in a laboratory or well-equipped site hut but require little in the way of specialist skills. Most of the equipment can be sourced through scientific suppliers or found in environmental science laboratories. They comprise some of the least expensive and most common lab-based techniques used in geoarchaeological analysis.

pH analysis

The pH of a deposit is a measure of its acidity or alkalinity (Fig. 13). Acidity is an important factor in the preservation conditions of a site, so analysis of pH is usually carried out to investigate the potential for preservation of certain artefacts and environmental evidence. For example, if a site, or one part of a site, has an unexpected absence of bones, pH readings taken systematically on a grid could help to determine whether this is the result of aggressive soil conditions or another process. Additional information and example applications are provided here.

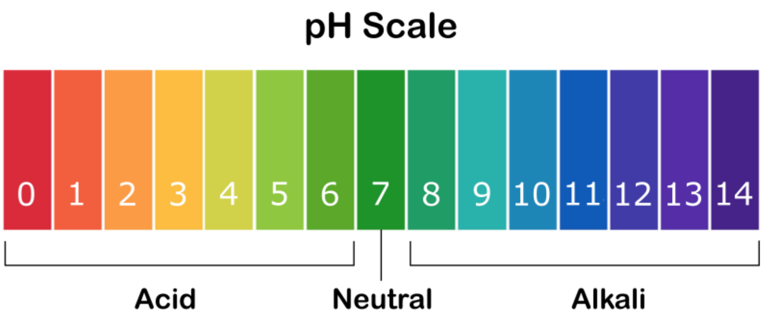


Fig. 13. *pH scale (image © Vanessa Reid)*

pH analysis is best conducted using a hand-held probe. These should ideally be sourced from a scientific supplier, as garden centre pH probes are often not accurate enough for archaeological purposes. pH paper is a cheaper alternative but again is a less accurate method of measurement.

Electrical conductivity (EC)

Electrical conductivity (EC) is a measure of how well a substance can conduct an electrical current. In soils and sediments, field measurements of EC are mainly affected by water content, which in turn is strongly influenced by texture (e.g. easily drained sands commonly have low EC, while clays have high EC). However, when water content is controlled in a laboratory setting (e.g. by drying a soil sample), EC can be used to measure the content of soluble salts (ions) that carry electrical currents. Materials high in soluble salts include urine, sea salt and seaweed, making EC a useful method for site activity area analysis when samples are taken systematically across a site (e.g. on a 1 m^2 grid). Although EC is not capable of determining which soluble salt is present, it can help to plan the next stage of more detailed geoarchaeological analysis (e.g. laboratory phosphate analysis or multi-element analysis).

Advice Note

EC analysis is conducted using a hand-held probe. Some probes combine pH and EC measurements, so these two tests can often be done at the same time.

Loss-on-ignition (LOI)

Loss-on-ignition (LOI) is the easiest, cheapest and fastest way of estimating how much organic matter a deposit contains. Organic matter includes all plant and animal tissues, from fresh to decomposed, and becomes enhanced in settlement areas through human and animal activity. Loss-on-ignition can therefore help to identify activity areas such as middens, fodder storage areas, animal pens, and areas involved in the use/disposal of organic building materials such as turf.

Organic matter also plays an important role in binding soil particles together and affects soil properties such as water holding capacity, structure and plasticity. Soils with low organic matter content are more susceptible to wind and water erosion, so LOI data can help to inform site management strategies. Organic matter content is elevated in topsoils and can therefore be used to identify buried soils and past landscapes. In peat deposits, the ratio of organic matter to mineral material is reduced when erosion causes an influx of sediment, so organic matter content can also be used to detect human impacts on the local environment (e.g. by de-vegetation and farming).

Loss-on-ignition is conducted on bulk samples that have been air-dried and sieved through a 2 mm mesh. The organic matter is burnt off (Fig. 14) when heated to a high temperature (550°C) and a method of the lab process is provided here. How and where these samples are collected will depend on the types of questions being asked. Some suggested strategies are below, however consultation with a specialist is encouraged if you are at all unsure:

- **Activity area analysis** – Take bulk samples from selected features or, preferably, on a gridded sampling scheme (on- and off-site) using a trowel or auger.

- **Buried soil identification** – Take samples from all visible horizons in a vertical profile, including above and below the possible buried topsoil.

- **Sediment influx identification** – Take small bulk samples systematically through a lake core or core/monolith from a peat bog. If possible, X-ray the core first to identify the layers with higher mineral content and density to help guide the subsampling.

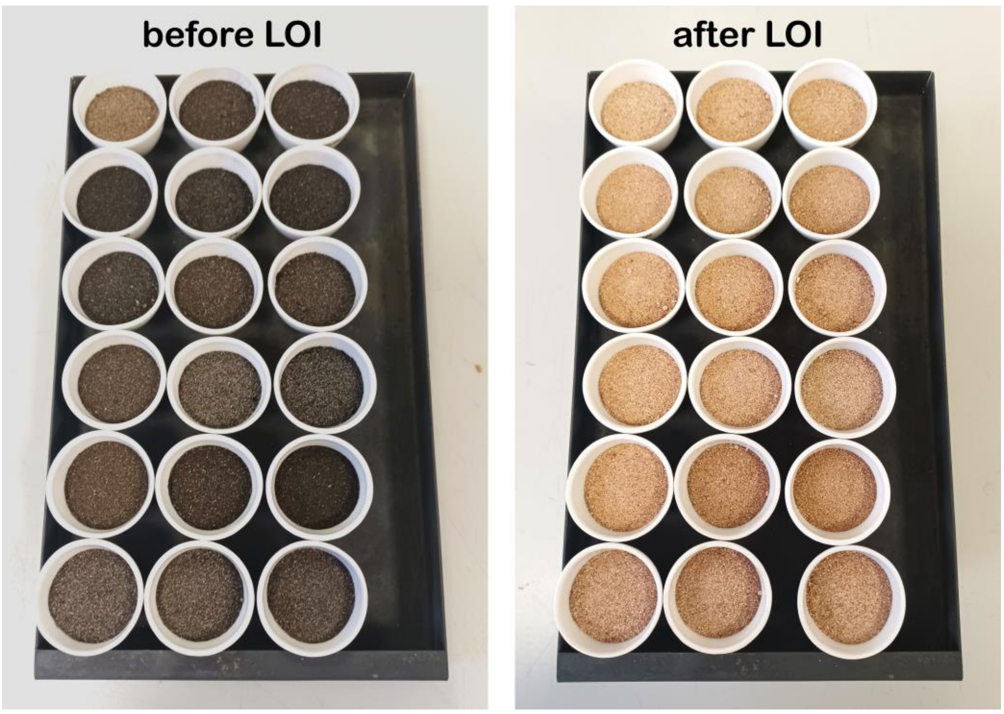


Fig. 14. *Before and after loss-on-ignition at 550°C – difference in colour is attributable to the lost organic matter content (photographs © Vanessa Reid)*

Case Study 4: Integrated Geoarchaeology of an Early Medieval Farmhouse

Lair is an upland settlement in Perthshire that contains a range of multi-period remains. Amongst these are two clusters of early medieval turf longhouses, of which Building 3 was the best preserved. Excavation revealed that the main interior space was divided into a living area on one end, and a byre area for housing animals at the other. A small annexe was also attached to the exterior.

Bulk samples from all areas (including the turf walls) were taken on a 50 cm grid. Standard laboratory methods of pH, EC, LOI and magnetic susceptibility were integrated with bone and charcoal distributions, and more specialist techniques of micromorphology and multi-element analysis, to allow for an in-depth assessment of site activities and preservation conditions.

pH analysis found that the site was highly acidic (pH 3.2-4.7) and explained why only burnt bone was recovered and why organic artefacts and unburnt bone were completely absent in the > 2mm bulk sediment fraction. Organic matter (LOI) and multi-element concentrations varied across the site but were notably elevated in the byre and the turf walls. Interesting, the organic composition of the walls varied between the longhouse and the annexe, suggesting that they were constructed at different times or that the wetter, more organic (and therefore better) turves were used for the longhouse construction. The integrated approach also revealed evidence for floor maintenance practices, identified divisions of space, and indicated that accumulations of organic matter in the byre likely came from animal feed, bedding and waste (Fig. 15).

An interesting point at this site was that floor layers were almost impossible to identify during excavation. The integrated laboratory analysis was therefore vital in confirming that a floor was preserved and proving that ephemeral floors still retained chemical signatures relating to their use.

Read more about this case study:

- Early Medieval Settlement in Upland Perthshire
- Research article (forthcoming)

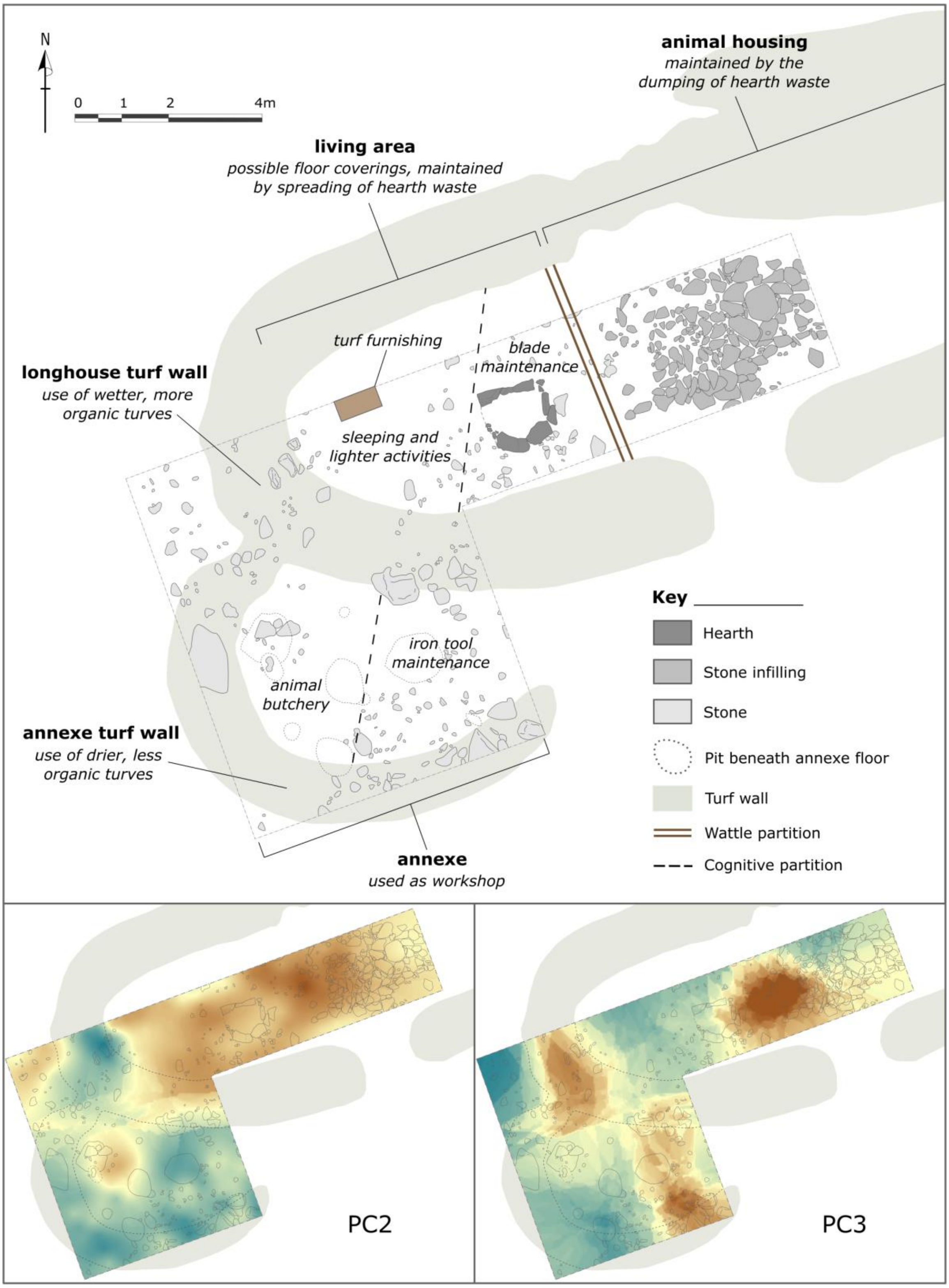


Fig. 15. *Interpretive plan (top) of Lair Building 3 based on integrated field evidence, geoarchaeological data and multi-variate statistical analysis (bottom) (image © Vanessa Reid)*

Particle-size analysis

Soils and sediments never contain just one size of particle, even those that are very well sorted. Particle-size analysis aims to group the particles which form a deposit into size classes (Table 3) to determine the relative proportion of each size fraction. Essentially, it is a more accurate measurement of a deposit's texture and degree of sorting.

Table 3: Particle size categories (adapted from definitions of the British Standards Institution and the SASSA Soil Recording Help Sheet)

Size range (mm)		Particle class
< 0.002		Clay
0.002 - 0.06		Silt
0.06 - 0.2	Fine	Sand
0.2 - 0.6	Medium	Sand
0.6 - 2	Course	Sand
2 - 6	Fine	Pebble
6 - 20	Medium	Pebble
20 - 60	Course	Pebble
60 - 200		Cobble
200 - 600		Stone
> 600		Boulder

As many sedimentary processes sort materials according to their size and weight, particle size is mainly used to determine the mode and energy of deposition. This can include establishing whether material was deposited by wind or water, and whether this was moving or stagnant water. It can be applied to discrete sedimentary layers or used to determine if there is a wind-blown sand component in a soil.

Sieving is the cheapest, easiest and most common way to assess particle size. It involves the physical separation of particle sizes through a stack of sieves and is particularly useful for the measurement of larger particles. The range of mesh sizes used will depend on the deposit but typically reduces to 2 mm. A general methodology is provided here.

Soils that are particularly rich in organic matter or clay may require additional pre-treatment. Further assessments of the fine fraction (silt and clay components) can be conducted by sending the 2 mm sieved sample to a specialist lab for laser particle-size analysis (at a cost of £20-40 per sample).

Specialist Techniques

There are occasions when the above suite of techniques cannot answer specific geoarchaeological questions or fail to provide the required detail. The following techniques are designed to fill this gap and need to be carried out by a specialist. Micromorphology can help to answer a broad range of questions about site formation, activities and preservation environments. Other methods focus on the collection of detailed mineralogical, chemical and biochemical data. Whilst powerful, these are some of the most expensive geoarchaeological techniques and it is strongly recommended that professional advice is sought at the beginning of a project to create appropriate sampling strategies and guide budgets.

Deposit modelling

Deposit modelling provides a visual representation of the soil and sediments beneath the modern ground surface. This includes information on the type, depth and extent of the layers. They are most often used when archaeological deposits have been buried by other sediments (e.g. wind-blown sand) and cannot be identified using standard geophysical survey.

Deposit models can be constructed as part of a desk-based assessment using existing borehole data but are most effective when combined with the results of deep geophysical survey, test-pitting or coring. This can then be used to interpret past environments, understand landscape processes and human activities, and locate areas with the greatest archaeological potential for future field investigation.

The resolution of the data points will depend on the questions being asked of the model, the nature and complexity of the buried deposits, and the size of any features that the model is aiming to identify. For this reason, deposit modelling requires good collaboration between the geoarchaeologist constructing the model and the supervising archaeologist, as well as with any end-users who need to understand and use the output.

Soil and sediment micromorphology

Micromorphology (also known as ‘thin-section analysis’) is the study of undisturbed soils and sediments under a microscope. It relies on lifting and processing whole blocks of intact sediment from an archaeological profile in order to retain stratigraphic integrity. These blocks are dried, embedded in resin, mounted on glass slides and thin-sectioned to 30 µm (Fig. 16). Trained users can then examine layers, components and soil features (pedofeatures) that are too small to be seen with the naked eye (Fig. 17).

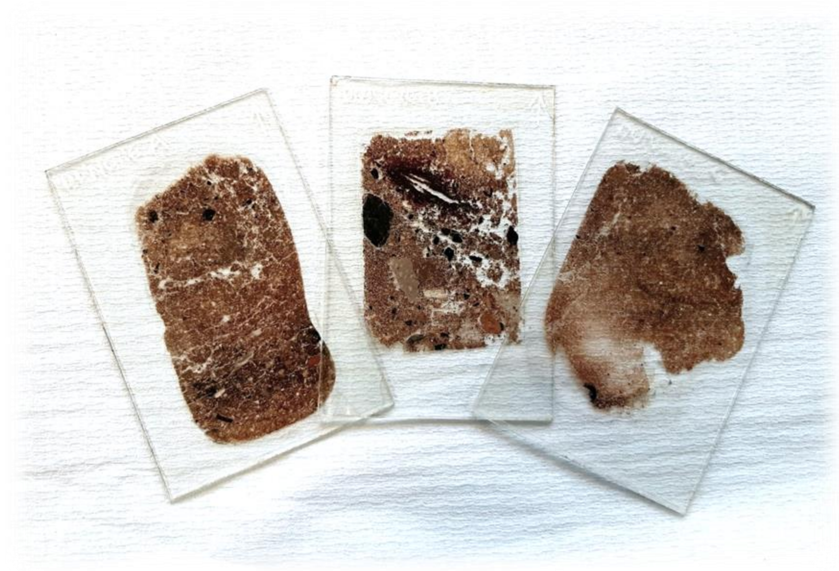


Fig. 16. *Manufactured thin-sections taken from Dunnicaer Pictish fort (Canmore [37001](37001) ; image © Vanessa Reid)*

Micromorphology complements the visual interpretations made in the field, often providing details that explain the features observed, or clarifies the soil or sediment's original composition, origins, and modes of formation. Importantly, it also provides information about the original orientation, distribution, and associations of microscopic artefacts and ecofacts that can otherwise only be recovered from sieved bulk samples.

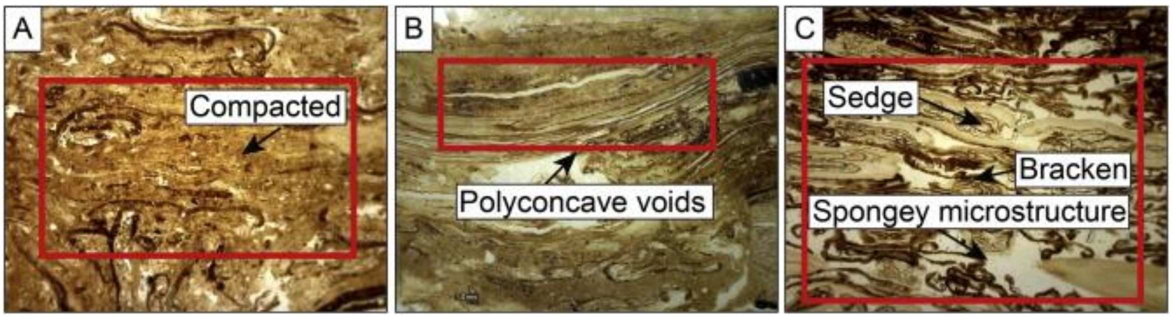


Fig. 17. *Examples of structural features and organic material identified in micromorphological thin-sections from Structure 2 at Black Loch of Myrton, Dumfries and Galloway (image © Mackay et al. 2020)*

The benefit of micromorphology is that it can provide key insights into a broad range of occupation events and site formation processes. For example, it can help to identify:

- cleaning practices and abandonment episodes
- midden and burnt mound formation processes
- cultivated soils and past agricultural practices
- trampled occupation surfaces, flooring materials and coverings, and the organisation and functions of activity areas
- construction materials and methods of building earthen structures
- post-depositional processes such as bioturbation, compaction and leaching

The success or failure of micromorphology is most often determined during the sampling stage. Samples that are taken incorrectly, from inappropriate contexts or have been poorly labelled can prove to be unusable. A step-by-step guide to sample collection has been provided in this document. It is recommended that professional advice is sought if you encounter a problematic deposit or are in doubt about how to collect samples.

Once collected, samples should be tightly wrapped, labelled and sent to a dedicated thin-section laboratory. Completed thin sections can then be sent to a trained micromorphologist, who will provide detailed descriptions of your soil or sediment and interpretations of the evidence. The manufacturing process alone can take a considerable period of time (often several months) and should be planned for if projects require rapid results.

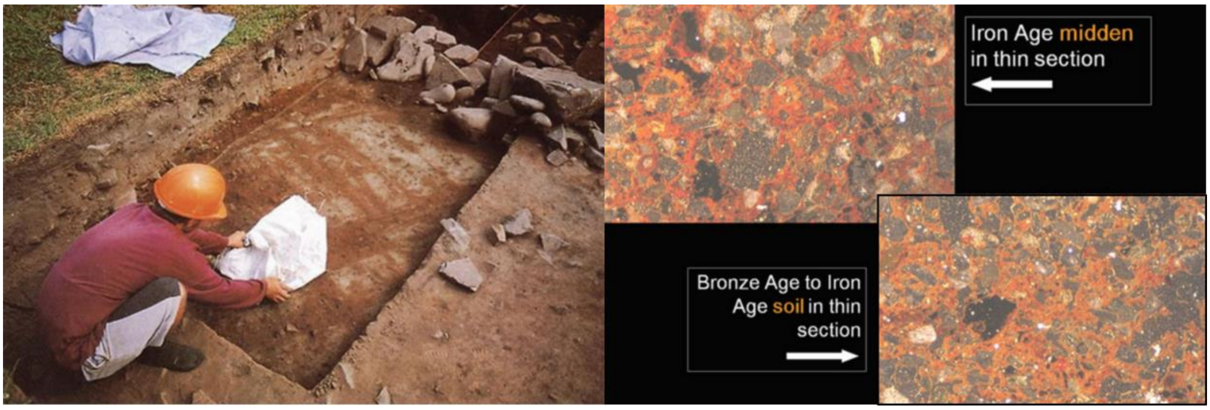


Fig. 18. *Excavating a midden at Old Scatness (top image © Val Turner); Iron Age soil and midden in thin-section under oblique incident light (bottom image © Erika Guttmann-Bond) – Case Study 5.*

Case Study 5: Managing Arable Lands in Prehistory

Old Scatness is a multi-period settlement site in Shetland that comprises a settlement mound and surrounding arable land. The site was subjected to major episodes of wind deposition, and these wind-blown sands buried and preserved successive agricultural soils together with the associated settlement evidence.

Geoarchaeological investigation at the site concentrated on understanding settlement activity and tracking changes to agricultural methods over time. Micromorphology was used to characterise the formation of floor layers and midden deposits, as well as identifying the anthropogenic materials that were added to arable soils. Phosphate analysis and particle-size distribution were also conducted on these deposits to find links between deposit types and assess the quantity of organic inclusions.

Analysis revealed that the arable soils were composed of exactly the same material as the midden heaps (Fig. 18). During the Neolithic and/or Bronze Age, domestic waste, hearth ash and floor material were recycled for use as soil fertiliser. During the Iron Age, there was a change in the type of fertilising materials used and the soils became much richer in phosphates and organic material. This indicated the inclusion of animal manure and, by the middle of the first millennium AD, manuring appeared to be an integral part of the fertilising strategy. The combined data was therefore evidence of a change in the relationship between arable farming and livestock husbandry and suggested that the settlement had developed their organisation of the resources required for agriculture.

Read more about this case study:

- Research article 1
- Research article 2

X-radiography of blocks and cores

Soil blocks and cores can also be subjected to X-ray photography (X-radiography) to assess their stratigraphic integrity before they are processed in the lab.

The image produced in X-radiography is related to the density of the sedimentary materials and shows differences in material composition (e.g. textural changes) or compactness. For example, a compact layer of clay or iron pan in a coarser profile will produce a thin pale band. It is therefore particularly effective in identifying zones of disturbance. However, because different constituents can produce visually similar effects (e.g. the clay and iron bands mentioned above), interpretation of a sequence cannot be made solely using X-radiography. Instead, this step is used as an aid to plan subsequent processing and analyses.

Phytolith analyses

Phytoliths are very small particles of silica (between 5 and 100 µm) that form within most plants (Fig. 19). They have distinctive shapes that can be used to identify the types of plants present at a site, and are particularly important as they persist in a soil or sediment long after the rest of the plant has been ashed or decomposed. Phytolith analysis is therefore very commonly used as a complement to micromorphological analysis to understand the decomposed plant component.

Phytoliths are examined using a microscope and can be analysed in thin-section (micromorphology samples) or specially processed bulk samples. How and where these samples are collected will depend on the types of questions being asked. Some suggested strategies are below, however consultation with a specialist is encouraged if you are at all unsure:

- **Activity area analysis** – Take block or bulk samples from selected features or, preferably, on a gridded sampling scheme (on- and off-site) using a trowel or auger.

- **Environmental reconstruction** – Take block or bulk samples from areas away from human occupation/disturbance. Samples can also be taken vertically through a soil profile to study changing frequencies of taxa over time.

- **Modern surfaces** – Bulk samples can also be collected from modern surfaces to create a reference collection. This can help detect if any phytoliths have move downwards through the soil or sediment profiles and contaminated archaeological strata.

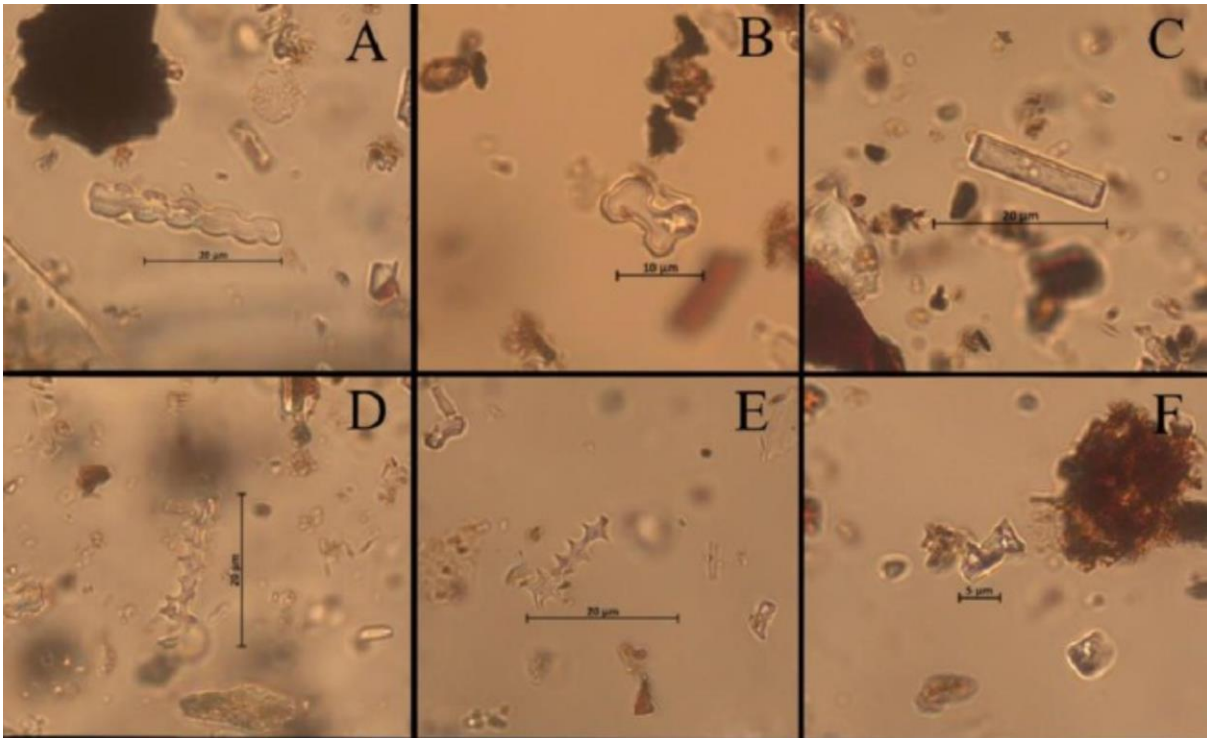


Fig. 19. *Phytoliths from the roundhouse floor at Cairnmore, Aberdeenshire (Canmore 17723; image © Prado and Noble 2022)*

Multi-element analysis

The elements within a deposit can tell us a lot about past human activity. Inputs from manuring, metalworking, hearths and industrial activities leave characteristic signatures that can be quantified using analytical chemistry methods. There are a range of different techniques, instruments and protocols available (e.g. ICP-AES, ICP-MS and XRF), all of which result in a precise and detailed quantification of a range of individual elements.

Applications are diverse and include:

- site prospection
- identification of distinct elemental signatures for infield/outfield systems
- assessments of manuring practices and soil pollution

- characterisation of the organisation and functions of activity areas

Although undoubtedly a powerful technique, the results of multi-element analysis can rarely be interpreted in isolation. Understanding the local soil environment is often essential, and projects that successfully employ multi-element analysis will typically assess other soil properties such as pH, EC, LOI or magnetic susceptibility.

Multi-element analysis only requires a few grams of soil or sediment that has been air-dried and sieved to 2 mm (Fig. 20). Analysis is most effective when samples are taken systematically across a site (e.g. on a 1 m^2 grid). It is also important to take off-site reference samples to evaluate the natural levels of elements and their variability (see Control Samples).

Fig. 20. *Pressed sediment pellets ready for multi-element analysis at University of Stirling (image © Vanessa Reid)*

Case Study 6: Post-Medieval Settlement Patterns

The abandoned rural townships of Perth and Kinross have provided a focus for experimental geoarchaeological research and the validation of multi-element analysis techniques. To date, studies have assessed past manuring practices, patterns of elemental enhancement in functional areas, and whether these signatures are site-specific or can be compared between sites.

One example of this research has been the multi-element analysis conducted on soils at Duallin township (Canmore 290580) as part of the Ben Lawers Historic Landscape Project. Soils collected from areas of settlement and arable agriculture were subjected to XRF and statistical analysis, which revealed significant differences for 18 chemical elements in the soils. Soil organic carbon (SOC) content and pH analysis were also conducted alongside the multi-element analysis, and the resulting data suggested that soils of former settlement and arable farming can be effectively classified according to their pH, SOC content and concentration of calcium, copper, magnesium, rubidium and zinc.

The identification of distinct elemental signatures for infield/outfield systems (Fig. 21) has significant implications for the prospection of similar sites, particularly in locations where perishable turf materials have been used and no surface remains survive.

Read more about this case study:

- Ben Lawers: An Archaeological Landscape in Time. Results from the Ben Lawers Historic Landscape Project, 1996–2005
- Research article

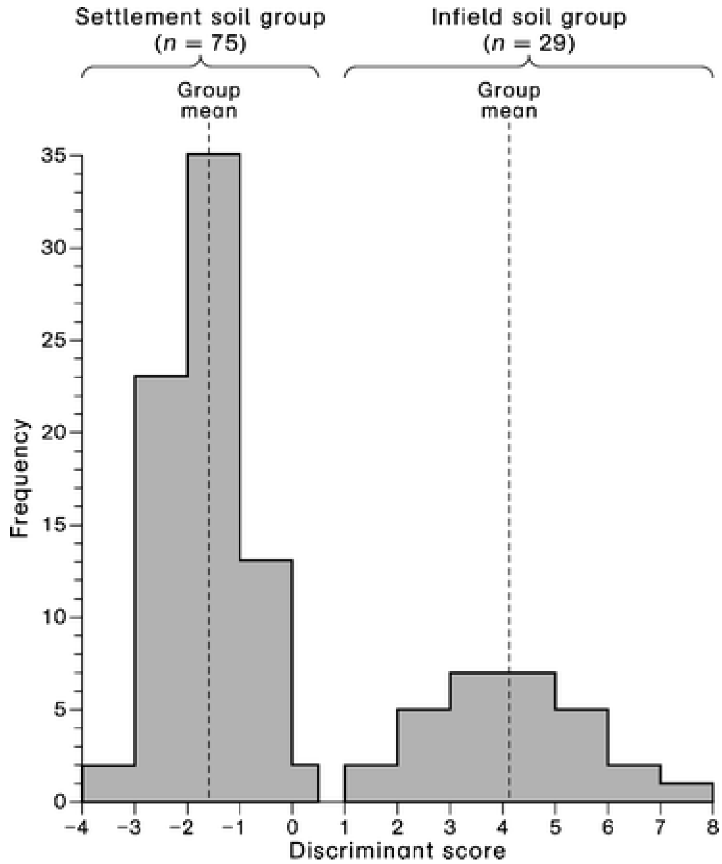


Fig. 21. *Discriminant scores for soils in the farming settlement at Duallin; analysis was 100% effective in correctly classifying the infield and settlement soils according to their pH, SOC content and total concentrations of Ca, Cu, Mg, Rb, and Zn (image © Abrahams et al. 2010)*

Biomarker analysis

Biomarker analysis (also known as ‘lipid biomarker’ analysis) is a branch of biochemistry that can identify the presence of plants and animals on archaeological sites and distinguish them to various taxonomic levels. The technique relies on the persistence of lipids, organic compounds that exist in biological inputs such as plant and wood matter, animal fats or faecal deposits. Lipids have a low solubility in water and bind to soil particles, meaning they can survive for a long time in soils and sediments, and are less prone to degradation than DNA. Biomarker analysis characterises the types and amount of lipids in a deposit, generating a ‘lipid fingerprint’ that can identify the taxa responsible. Example applications include:

- detection of animal pens and their occupants
- identification of manuring practices

- taxonomic identification of faecal material, plant and wood residues, and animal-derived fats
- characterisation of the organisation and functions of activity areas
- identification of latrines and sewage channels
- analysis of fuel and food processing areas

Sampling for biomarker analysis requires additional protocols to limit contamination. Notes on these procedures have been provided later in the document (see [Biomarkers and sedaDNA]), however specialist advice should always be sought prior to sampling.

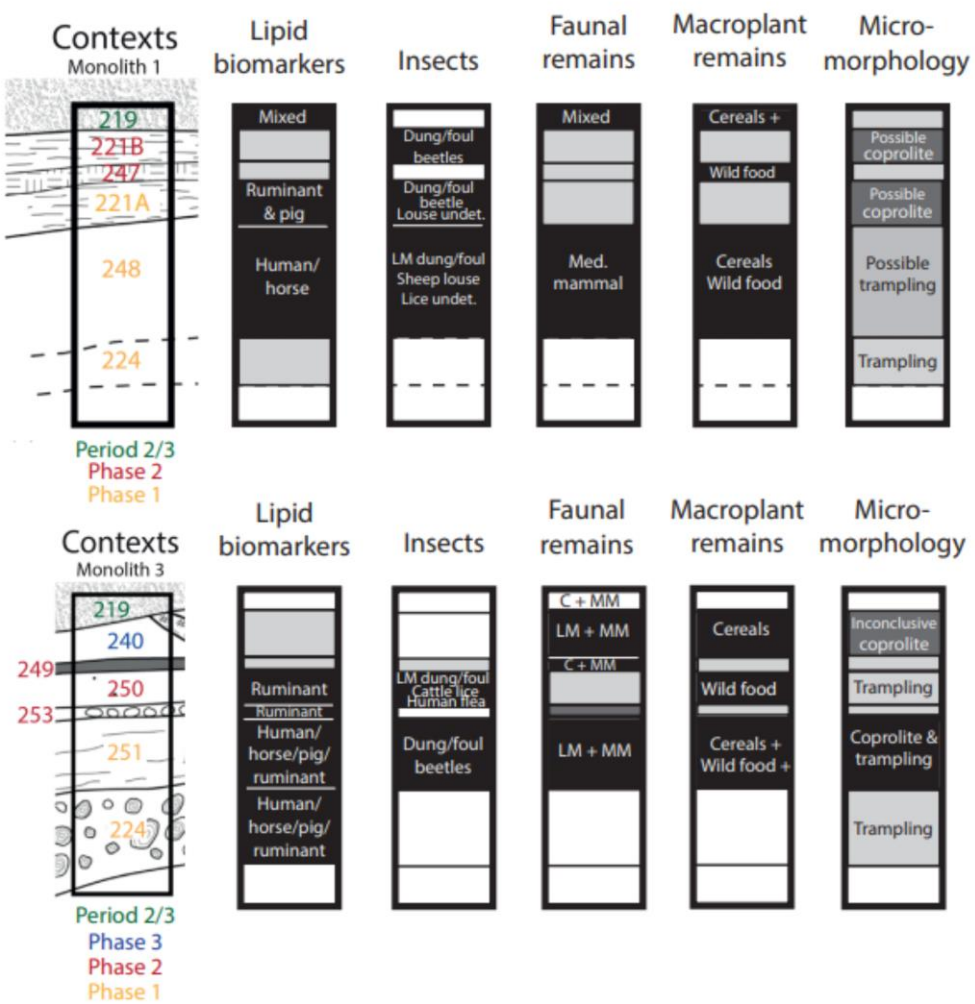


Fig. 22. *Integrated proxy evidence for settlement activity at Black Loch of Myrton – Case Study 7; black indicates clear evidence of large mammals, faecal sources or domestic food waste (image © [Mackay et al. 2020])*

Case Study 7: Settlement Life and the Division of Space

Black Loch of Myrton is Scotland's first example of an Iron Age wetland village. It was occupied from the 5th to 3rd centuries BC and waterlogging at the site has resulted in the excellent (and extremely rare) preservation of structural remains and organic material. Sites like this have huge potential to enlighten poorly understood parts of the archaeological record, such as household activities, living conditions and animal management strategies.

Faecal lipid biomarkers were studied in one of the roundhouses and integrated with more traditional indicators of animal activity, such as insects, bones and plant macrofossils (Fig. 22). The biomarkers suggested that there were short-lived episodes of dung deposition within the roundhouse, which are usually very difficult to determine using the more traditional methods. The biomarkers could also be picked up in areas of trampling and cleaning, which would usually remove larger remains such as plant and bone macrofossils.

The biomarkers also provided evidence for the division of space, suggesting that animals were temporarily sheltered within the inner section of the structure. Although roundhouses are widespread across north-west Europe, the use of their internal space remains poorly understood and evidence for this division marks an important development in Iron Age research. This study shows just how much new techniques are contributing to interpretations, not only in Scotland but across the continent.

Read more about this case study:

- Research article

Sedimentary ancient DNA

Sedimentary ancient DNA (also known as *sed*aDNA or environmental aDNA) refers to the genetic material held within soils and sediments. This is different to most ancient DNA, which is held within physical remains such as bones, teeth and hair. Because of this difference, the sources of *sed*aDNA cannot be definitively known, however they are most likely to originate from plant matter, fungi, microbes, animal tissues, hair, urine and faeces.

Similar to biomarker analysis, *sed*aDNA analysis is a biochemical technique that can identify organisms on archaeological sites and distinguish them to species level. It is most commonly used in the analysis of lake cores. Contamination is a major concern for ancient DNA analysis, and specific sampling procedures are required. A specialist should always be consulted prior to this process.

Sedimentary DNA analysis is among the most expensive techniques available and applications in Scotland are rare. Nevertheless, it is a novel technique that harbours great interpretative power and future examples are likely to showcase the huge potential of Scotland's archaeological soils and sediments.

Summary of geoarchaeological methods

Table 4: Summary of common analytical methods in geoarchaeology

	Scale of investigation	Sample type	Time / Cost (£-££££)	Typical applications
Desk-based resources	National, regional, landscape and site scale	Requires locational information (grid reference, GPS data, postcode etc.)	Instant results Free to use/download	▪ Site prospection ▪ Assessment of site/landscape geology and soil conditions ▪ Assessment of past and present land-use ▪ Evaluation of risks to site integrity
Field descriptions	Landscape, site, structure and feature scale	Exposed soil or sediment profile, cores	Very quick No cost once the field equipment is purchased	▪ Characterisation of site stratigraphy and landscape ▪ Primary interpretation ▪ Identification of site formation processes
Phosphate	Landscape, site and structure scale	Small bulk sample (c. 200 ml) (sample prep depends on method used)	Very quick to moderately quick £-££ (field methods cheaper and faster than lab methods)	▪ Site prospection ▪ Identification and characterisation of manured soils and activity areas
Magnetic susceptibility	Landscape, site and structure scale	Field test: Exposed surface, sediment profile or auger hole Lab test: Small bulk sample or sub-sampled core (air-dried, sieved 2mm)	Very quick to moderately quick (individual sample analysis takes just a couple of minutes) ££	▪ Site prospection ▪ Identification of areas of burning or burning residues ▪ Identification of buried soils ▪ Assessment of soil processes such as waterlogging and microbial activity

pH	Site and structure scale	Small bulk sample or sub-sampled core (air-dried, sieved 2mm)	Very quick (individual sample analysis takes just a couple of minutes) £	▪ Investigation of taphonomy and artefact/ecofact preservation ▪ Assessment of deposit type
Electrical conductivity	Site and structure scale	Small bulk sample or sub-sampled core (air-dried, sieved 2mm)	Very quick (individual sample analysis takes just a couple of minutes) £	▪ Site prospection ▪ Assessment of deposit type ▪ Identification of areas with elevated salt or nutrient content
Loss-on-ignition	Landscape, site and structure scale	Small bulk sample or sub-sampled core (air-dried, sieved 2mm)	Moderately quick (usually 1-2 days per batch) £	▪ Identification of buried soils ▪ Identification of sediment flux in peat sequences ▪ Identification of activity areas with higher organic content ▪ Investigation of taphonomy and artefact/ecofact preservation (e.g. pollen and plant macrofossils)
Particle size	Landscape and site scale	Large bulk sample, c. 1 kg (air-dried; organic or clayey soils may require additional pre-treatment)	Moderately quick (usually 1-3 days depending on pre-treatment and methods used) £-££	▪ Establishing mode and energy of sediment deposition ▪ Identification of landscape processes
Deposit modelling	Landscape and site scale	Requires locational information for desk-based assessment Cores and/or test-pits required for models following fieldwork	Analysis can take weeks to months, depending on the complexity and number of data points £££	▪ Identification of buried soils ▪ Identification of areas of high/low archaeological potential ▪ Informing excavation strategies ▪ Identification of past landscape processes ad human activities

Micromorphology	Landscape, site, structure and feature scale	Undisturbed blocks, well-sealed, with original orientation marked Specialist advice is recommended prior to sampling.	Processing and analysis take several months £££	▪ Characterisation of soil and sediment composition and structure ▪ Interpretation of origins and development processes ▪ Identification and characterisation of microscopic layers, orientations and distributions ▪ Identification of post-depositional processes and artefact/ecofacts preservation conditions (e.g. bioturbation, leaching, compaction)
X-radiography	Site and structure scale	Undisturbed block or core	Analysis takes days to weeks £££	▪ Understanding of deposit formation or hiatuses ▪ Identification of disturbance ▪ Aid to plan subsequent processing and analyses
Phytolith	Landscape, site, structure and feature scale	Undisturbed block or core; small bulk sample (could be sub-sampled from block or core)	Analysis takes weeks to months £££	▪ Characterisation of activity areas ▪ Interpretation of individual features/deposits ▪ Palaeoenvironmental reconstructions
Multi-element	Regional, site, structure and feature scale	Small bulk sample or sub-sampled core (air-dried, sieved 2mm)	Very quick to moderate (individual sample analysis can take as little as 5 minutes but interpretation and statistical analysis of larger datasets will take longer) ££-£££ (individual samples are cheap but require a lot of replicates)	▪ Site prospection ▪ Study of past pollutant/input events ▪ Identification and characterisation of activity areas ▪ Interpretation of individual features/deposits

Biomarkers	Landscape, site, structure and feature scale	Small bulk sample or subsampled core (using clean tools and gloves) Specialist advice should be sought prior to sampling.	Analysis takes weeks to months £££	▪ Palaeoenvironmental reconstructions ▪ Identification of manure, plant, or fat inputs ▪ Characterisation of activity areas ▪ Interpretation of individual features/deposits
*Sed*aDNA	Landscape, site, structure and feature scale	Small bulk sample or subsampled core (using clean tools and gloves) Specialist advice should be sought prior to sampling.	Analysis takes weeks to months ££££	▪ Palaeoenvironmental reconstructions ▪ Identification of any decomposed organic remains, including

Practical Advice on Geoarchaeological Analysis

This section focuses on some of the practicalities of geoarchaeology, including what to include in soil and sediment descriptions, how to assess soil texture, how to recognise different depositional agents in the field, examples of sampling strategies, and a step-by-step guide for how to take micromorphology, biomarker and *sed*aDNA samples.

Describing soil and sediments

Good field descriptions are the key to robust geoarchaeological interpretations and meaningful interpretations. They are particularly important for techniques which examine stratigraphy in detail, such as deposit modelling and micromorphology. The following summaries provide a brief overview of what should be included in field descriptions, and what they can tell us about a deposit. More specific information on how to record deposit features can be found in the SASSA Soil Recording Help Sheet.

General – Providing general notes on a deposit's setting and burial conditions may seem obvious but can play a key role in the interpretation of more detailed observations. Notes should include information on location (e.g. on a ridge, floodplain or terrace), drainage conditions and any obvious disturbances. These types of notes are also incredibly useful if records are consulted by an outside party or revisited after a considerable period of time.

Colour – Colour is the most obvious deposit characteristic and is often the best indicator of stratigraphic boundaries. As a deposit's colour is directly influenced by its underlying geology, organic matter content, iron content and moisture levels, it offers an excellent insight into these properties. Descriptions can be achieved using general terminology (e.g. light reddish brown), however Munsell Soil Colour Charts provide a more standardised way to record colour data (Fig. 23). Their use is preferred for geoarchaeological descriptions and when publishing section drawings or site plans.

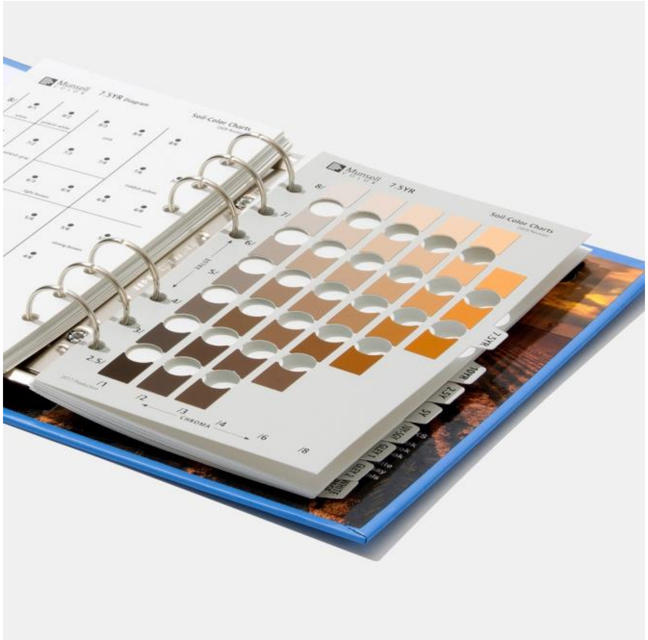


Fig. 23. *Munsell Soil Colour Chart (image © Pantone)*

Texture – Texture refers to the relative proportions of sand, silt and clay in a deposit. It is one of the best ways to identify a sediment's origin and can also help to recognise different sediments in a profile when colours or inclusions are indistinguishable. Texture can be assessed by hand-texturing, which involves taking a small handful of soil or sediment, adding enough moisture to make it mouldable and working it with your fingers into a series of shapes. A guide to this process is provided in the following section of this document. In general, sandy deposits feel gritty, silty deposits are smooth, and clays tend to be sticky.

Sorting – Sorting refers to the distribution of different particle sizes in a deposit. Particle size (or grain size) is a measure of the diameter of individual grains of sediment, which can range from microscopic clay particles to large boulders. A well-sorted deposit will only contain particles of a similar size, while a very poorly sorted deposit will contain a wide range of particle sizes (Fig. 24). Natural agents of deposition such as wind and water sort sediments differently according to their particle size, so the degree of sorting offers further information on depositional processes (see Identifying Sedimentary Processes in the Field).

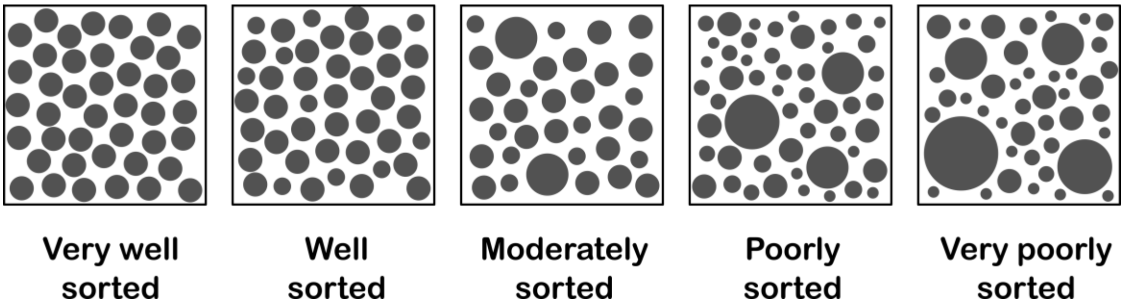


Fig. 24. *Degree of sorting (image © Vanessa Reid)*

Rounding – Particle rounding can result from abrasion during wind and water transport. Stones, pebbles and sands that have been carried over long distances often have a more polished or rounded appearance and so the degree of rounding provides insight into a sediment's mode and distance of transport. Artefacts transported in a soil or sediment, including those moved around in ploughed soils, can also display rounding.

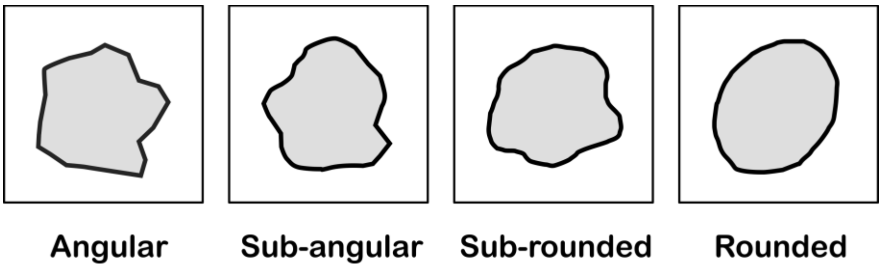


Fig. 25. *Degree of rounding (image © Vanessa Reid)*

Structure – Structure refers to the way in which soil particles clump together. The shape of these aggregates or 'peds' provides information on soil forming processes and deposit modifications such as bioturbation, wetting and drying, compaction by trampling, the formation of ice lenses in frozen soils, and any other forces that press and bind soil particles together. Structure cannot be reliably assessed in cored samples.

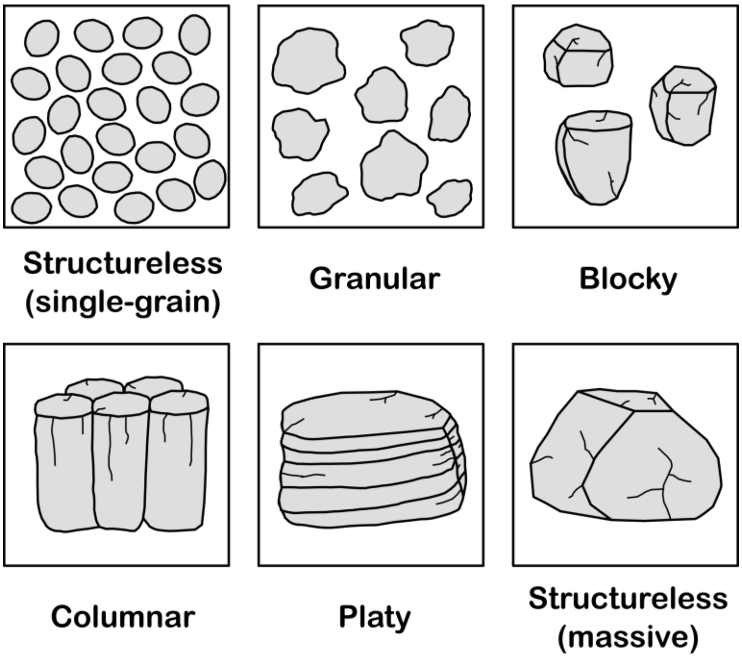


Fig. 26. *Types of soil structure (image © Vanessa Reid)*

Inclusions – Providing additional detail about soil inclusions is also incredibly helpful when interpreting depositional processes. This can include the shapes, sizes, degree of rounding, and the frequency of different inclusions such as charcoal, bones, shells or stones. Estimations of frequency are best made using visual percentage charts, such as those available at the front of Munsell Soil Colour Charts or in the SASSA Soil Recording Help Sheet.

Pedofeatures – Soil features (or 'pedofeatures') are found in all soils, including archaeological deposits that have been exposed to normal soil formation processes (all open-air sites). They provide information about the original composition of the archaeological deposits and how they have been impacted by post-depositional processes. Pedofeatures often influence a soil's colour and can include crystals of calcium carbonate (white) or vivianite (blue), manganese nodules (black), iron nodules (rust-coloured) or horizontal bands of iron-cemented soil known as 'iron pans'. Other types of pedofeature include coatings of clay, iron or organic material on particles or peds, as well as earthworm channels or animal burrows.

Hand-texturing

Hand-texturing (also known as field- or finger-texturing) is a technique that assesses the proportions of clay, silt and sand particles in a soil or sediment. It involves taking a small handful of soil or sediment, gradually adding moisture until it is easily mouldable (known as the 'plastic limit'), and working it into a series of shapes. How easy or difficult the sample is to mould and bend then determines the composition of the deposit. The flow chart below takes you through this process (Fig. 27).

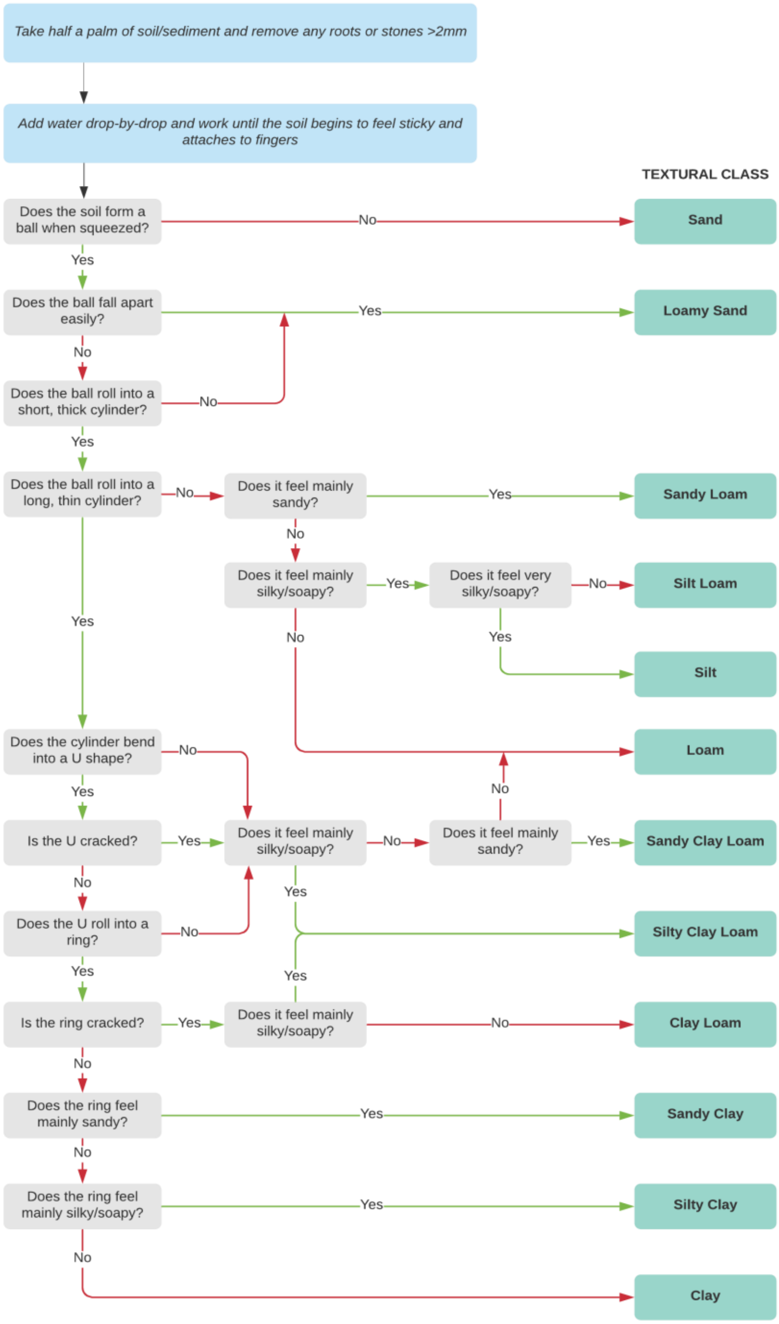


Fig. 27. *Flow chart of hand-texturing process (image © Vanessa Reid)*

Identifying sedimentary processes in the field

Table 5: Key characteristics of common sedimentary processes

	Landscape setting	**Colour**	**Particle size**	**Sorting**	**Structural features**	**Other**
Human-made deposits (anthropogenic sediments)	Found in all archaeological sites where material has been deposited by people, their animals, or where human-made structures have collapsed	Can vary in colour depending on the source material and how it was made	Typically a mix of different particle sizes (can range from clay to boulder-sized particles)	Usually poorly sorted, but depends on source material (e.g. an ash dump with few inclusions can be relatively well-sorted)	Degree of bedding structure varies depending on how rapidly the deposit accumulated (e.g. single-phase levelling deposits or grave fills may be a single stratigraphic unit, gradually accruing floor deposits typically have fine horizontal bedding, and midden deposits can have thick or thin bedding that is horizontal or tilted)	Deposits may be rich in artefactual and ecofactual material, construction materials, and environmental evidence such as phytoliths
Slope deposits (colluvium)	Typically found at the base of slopes or where there is a break of slope	Often brownish due to inclusion of topsoil material, but will vary depending on the source	Typically a mix of different particle sizes (depends on the nature of source material)	Usually poorly sorted	Poor internal stratigraphy, although sorted stone lines may be present Bedding is absent or weakly developed	Artefacts may be fragmented and abraded, with a weak downslope alignment Thickening of deposit towards base of slope
Flowing water deposits (alluvium)	Typically found in river or stream beds, floodplains, and ditches	Can vary in colour depending on source material and subsequent waterlogging or exposure to air	No diagnostic particle size, as deposition depends on the energy of water flow (higher energy water will deposit larger particle sizes)	Generally well-sorted	Some degree of bedding structure resulting from water flow energy and direction change (alluvial fans and channel deposits often display cross-bedding, whilst floodplain deposits tend to build up in parallel horizontal units)	Particles of all sizes are often rounded and smooth (indicating transport over long distances) Deposits that remain waterlogged for long periods may be rich in environmental

						evidence, such as phytoliths, pollen, insects or molluscs
Standing water deposits	Typically found in flat or depressed areas with impeded drainage, including moats, ditches, ponds, bogs, cellars, or any structure that captures water and causes it to puddle; can also form in standing structures or caves from dripping water	Can vary in colour depending on source material, amount of organic matter accumulation, and subsequent waterlogging or exposure to air	Typically fine-grained (primarily clays and silts), but depends on the source material	Moderately well-sorted to well-sorted	Likely to be laminated due to punctuated influx of water and sediment, often with grain size gradually decreasing towards the top as finer grains settle on larger, heavier grains (known as 'upwards fining') Bedding may be present	Unlike material transported in moving water systems, stones will not display rounding because they are likely to have been dumped or fallen in Can be rich in environmental evidence (phytoliths, pollen, insects or molluscs) if deposits remained waterlogged for long periods
Windblown deposits (aeolian)	Typically found on and near coasts, but can occur in any windy location	Often light in colour (consistent with nearby dunes if transported from coastal settings)	Fine-grained (fine sand and silt-sized)	Very well-sorted	May show lamination and cross-bedding resulting from wind flow energy or direction change, especially in dune environments	Individual grains will often be rounded, but are rough rather than smooth pH may be neutral to alkaline if the deposit contains fragments of marine shell (calcareous sands)

Choosing a sampling strategy

Sampling is an essential part of geoarchaeology and there are a variety of different sample types (test-pits, cores, blocks and bulk samples) that are used to study both vertical sequences and spatial variability (horizontal sequences). Different techniques require different sample types (Table 4) and the approach should consider the research questions asked, excavation and recording strategy, budget, timeframe, and access to equipment, storage facilities, and specialist analysists. Sampling should therefore always be planned in advance and should aim to address specific questions about site formation, use or human-landscape interactions. The exact approach will often change once excavations are underway, however without a research plan the analysis of samples is unlikely to be effective or good value for money. Handing a bag of sediment to a geoarchaeologist with the vague question 'what is this?' is likely to lead to disappointment.

Below are some examples of how a site may be sampled for geoarchaeological analysis. Most sites will involve a combination of these methods and, as each excavation comes with its own research questions and parameters, these are only intended to give an idea and are by no means prescriptive. Consultation with a [specialist or Local Authority Archaeologist] is encouraged if you are at all uncertain about sampling strategy or resolution.

Judgemental – Also called 'spot' sampling, this method involves taking samples from certain areas of a site in order to answer specific questions. These are most often employed when geoarchaeology is intended to help interpret a specific deposit or site formation event – for example, using particle size analysis to understand ditch fills. These can be micromorphology samples pressed down into a context (Fig. 28) or taken from a vertical profile or temporary baulk, monoliths taken from a profile, or bagged bulk samples. The latter may be sub-divided for a range of geoarchaeological and environmental analyses, so may need to be large (2-10 L) and include replicates where possible. For geoarchaeological analyses alone (e.g. if samples for flotation, sieving, or insects are taken separately) it is not necessary to take large bulk samples. 200 ml in total is sufficient for the full range of specialist techniques except for particle-size analysis of course or poorly-sorted sediment, which requires samples of roughly 1 kg.

Fig. 28. *Judgement-based micromorphology sampling pressing down into horizontal surfaces at Bhiliscleitir Shieling, Isle of Lewis (image © Karen Milek)*

Grid – This is a systematic method of horizontal sampling across an area, structure or context for the purpose of site prospection or the identification and characterisation of activity areas (Fig. 29). Grids can be used to locate test pits or direct the collection of cores, bulk samples or field magnetic susceptibility data. The resolution will depend on the area of study and the information sought, but intervals are generally between 1 m and 20 m across sites and between 0.5 m and 1 m within individual structures.

Fig. 29. *Grid sampling for microrefuse, magnetic and geochemical sampling at Burghead Pictish fort, Moray (Canmore 16146; image © Gordon Noble)*

Radial – Radial survey is another systematic sampling method where samples are taken at regular intervals along transects that radiate out from a point of known archaeological significance. This is most commonly used for phosphate and chemical analysis as a means of identifying the limits of a site or feature.

Profile – Sampling systematically from the stratigraphy identified in vertical profiles can provide helpful information about the temporal sequence of site formation. Sampling can take the form of micromorphology samples (Fig. 30), bagged bulk samples or monoliths depending on the research questions and the nature of the material (e.g. tins can be difficult to insert in soil or sediment with abundant bone or stone inclusions). Detailed guidance for how to collect these samples has been provided below.

Fig. 30. *Profile sampling through construction and activity deposits within Structure 1 at Ness of Brodgar, Orkney (Canmore 269123; image © Jo McKenzie)*

Taking Samples

There are several different sample types used in geoarchaeological investigation. Ensuring that samples are taken correctly will improve the success of geoarchaeological interpretations and avoid costly mistakes. Whilst most archaeological companies produce their own sampling guidance, the sections below cover important points specific to geoarchaeological analyses.

Biomarkers and sedaDNA

One of the main issues of biomolecular analysis is the contamination of samples. This can come from low-quality plastic bags used for sampling or the chemicals present on your skin. Samples are ideally collected in sterile glass bottles, although this is not always practical given their fragility, weight and cost. The most important point is to never directly touch a sample with your bare hand and use lab gloves (nitrile or latex) when collecting material.

The steps below are designed to guide you through the typical sampling process for lipid biomarkers. This type of sampling should only occur once an appropriate sampling strategy has been developed, and consultation with a geoarchaeologist or geochemist is strongly recommended.

1. Wearing nitrile or latex gloves, use a clean metal spatula or trowel to collect your chosen soil or sediment. It is best to clean the instruments with a tissue and some ethanol/acetone. Cleaning should be done between each sample.

2. Label your sample bag or bottle with the context number and any information relating to why you took the sample.

3. Dry the samples as soon as possible. Soils and sediments are active ecosystems that contain a wealth of microbes, so the sooner you dry them, the less chance that their chemical fingerprint will change due to bacterial activity. The best option is freeze-drying but they can also be oven-dried them (no more than 40°C) or air-dried.

4. Once dried, samples can be stored in a fridge or at room temperature, ensuring they are protected from light.

Micromorphology

Micromorphology samples are intact blocks of soil or sediment cut from the face of a clean vertical section. They can also be cut from the top of the target context if no sections are available, however a vertical profile is preferred.

Samples should ideally be taken using small aluminium boxes known as ‘Kubiena tins’ (Fig. 31). These are sharp, easily pressed into the soil, and hold the sample together (particularly important for crumbly, friable soils). Dense, consolidated soils or sediments (e.g. those rich in clay or organic matter) can be cut from a section without a tin, using a sharp trowel or knife. These are then wrapped tightly with cling film (food wrap) and packaging tape.

Fig. 31. *Kubiena tin (left) and examples of micromorphology sampling with tins (centre) and without tins (right) both at Ness of Brodgar, Orkney (Canmore 269123; images © University of Stirling and Jo McKenzie)*

In sites with deep stratigraphy, it can be more practical to take larger columns of sample. These are collected as above using metal monolith tins. These columns or monoliths can then be subsampled in a laboratory using Kubiena tins. Likewise, soil cores extracted using a mechanical (percussion) auger can be subsampled in the laboratory, making it possible to obtain micromorphology samples from buried sites, buried soils and large earthworks that are only accessible by coring.

Kubiena tins can be purchased from most micromorphology processing laboratories. They can also be made relatively simply in any workshop by cutting and bending 1.2 mm sheet metal into 9 (H) x 6 (W) by 4 (D) cm rectangular boxes with overlapping ends on a short side (the overlap must be taped together to give the tin rigidity) or by slicing aluminium drain pipes with square or rectangular cross-sections. Empty aluminium Spam tins can be used in an emergency, but are not ideal as they have a sealed bottom which can make it more difficult to properly embed the samples in resin. Steel electrical socket boxes are not a good alternative because they are very difficult for thin-sectioning laboratories to cut, and non-galvanized versions can rust in storage. Plastic boxes cannot be used because they dissolve in the acetone that is often used to thin the embedding resin.

The steps below are designed to guide you through the typical sampling process for an archaeological section. Micromorphology sampling should only occur once an appropriate sampling strategy has been developed, and consultation with a geoarchaeologist is strongly recommended if you are uncertain.

1. Clean back the section so that all horizons are clearly visible. Ensure it has been photographed and drawn at a 1:10 scale, and fully described. In most cases, the section should extend into the parent material (natural) below the site to capture the full extent of archaeological activity and the interface with the underlying soil.

2. Use a permanent marker to mark the side of your tin with an arrow pointing up. If you are not using a welded tin, bind the overlapping ends tightly together with masking tape.

3. Identify the best place to insert the sample (avoiding pebbles or bones that will prevent the tin from going in) and gently but firmly push the tin into the section. Use the flat of your trowel (or tin lid) to apply pressure if needed. Avoid the temptation to apply excessive force or to hammer the tin into place, as the vibrations can disrupt the structure of the sample. Continue until the tin is completely filled with soil. The edges of the tin facing you should be flush with the section.

4. If a section requires more than one tin to capture the profile, they should be overlapped as shown in Fig. 32. This avoids missing any horizons which may not be visible in the field and provides more data for each of the overlapped horizons.

Fig. 32. *Overlapping Kubiena tins during micromorphological sampling of a pit fill at Lair, Perthshire (Canmore 29509; images © PKHT)*

5. Before removing the blocks, ensure they are photographed *in situ* with an appropriate scale. Measure their height and location in the profile and mark this on the section drawing.

6. Gently remove the blocks from the section one at a time by inserting a trowel or knife behind each tin and using it to pry the block forward. Remove any excess soil material that is protruding from the edges of the tin and attach the lids (if using). If it was not possible to insert the tin all the way into the section because it was stopped by a stone, bone or artefact, the empty part of the tin should be filled until it is flush with the edge of tin using either cling film or an obviously different, sterile sediment (sand is best if it is at hand).

7. Mark the orientation and sample number on the lids, as well as on the sides of the tin. If it was necessary to artificially fill the tin, mark this on sides as well. If a large inclusion was protruding from the back of the block when it was extracted, it is often better to leave it in place, and to wrap the block tightly with plastic food wrap (cling film) and packaging tape.

8. Securely wrap each of the samples using cling film and packaging tape. Mark the site code, sample number, context number, up arrow, and any other notes on the outside wrappings.

9. Samples should be submitted for processing as soon as possible in order to maintain stratigraphic integrity. If this is not achievable, they should be stored in a refrigerator to limit biological activity. The samples should never be stored in a freezer, since expanding water disrupts soil structure. For shipping, samples should be packed in a ridged cardboard box with plenty of bubble wrap to prevent them from moving during transport.

10. Note that you must usually obtain a quotation from the thin-sectioning laboratory before submitting the samples. You will be asked about the size of the glass slides you would like used (which depends on the size of your blocks), and about how you would like the samples to be dried prior to embedding with resin. Sandy and loamy soils are best treated by air drying. Samples rich in clay or organic material (peaty soils) will shrink if air dried, so should be dried using acetone replacement of water.

Control samples

Control or reference samples are another type of geoarchaeological sample and are particularly important for chemical, magnetic, and biomarker analyses. They are taken 'off-site' (away from the area of archaeological interest) to provide a comparison with background levels and variations in 'natural' soils. Control samples should be taken from a location with similar characteristics to the study site (e.g. topographical position, parent material and drainage conditions) and must be collected and analysed in exactly the same manner as on-site deposits.

Identifying suitably 'natural' control samples can be problematic in built-up or intensively used environments (e.g. farmland). Where off-site areas are not suitable, wider sampling of the investigation area can be conducted in order to provide a 'site-average'. Being unable to source off-site control samples does not mean that geoarchaeological analysis cannot occur, as intra-site comparisons may be sufficient.

Conclusion

Geoarchaeology is an approach to archaeological data that encompasses a wide range of desk, field and lab-based activities to better relate the surviving archaeological record to human behaviour and its landscape. The techniques and resources outlined above are designed to give an insight into some of the most common methods used in geoarchaeology, however there are many other aspects of geophysics, geomorphology and soil science that fall under the umbrella term and highlight the multi-disciplinary nature of this approach. Geoarchaeology contributes to archaeological understanding at a variety of different scales and can have implications for our understanding of the human past far beyond site, regional or national borders.

The examples and case studies presented in this guide demonstrate the breadth of research in Scotland, and the country continues to prove itself as a world leader in the application and development of archaeological science. The routine consideration of geoarchaeology within the planning, evaluation and excavation of all types of archaeological project would help achieve a greater contextual understanding of their results and improve environmental sampling more broadly. As much of the sampling and sectioning required for geoarchaeological investigation will already be planned for, the discipline is primed for wider integration.

As with all scientific techniques, it is important to include geoarchaeological questioning at the *beginning* of a project. It is inevitable that strategies will change once new data is recovered, however understanding the limits and application of each technique is vital to avoiding costly mistakes or misdirected sampling. This guide is intended to help avoid such pitfalls; however, it does not replace specialist advice and consultation with an outside party is encouraged when you are at all unsure. Applied correctly, geoarchaeology is a powerful approach that allows us to direct, support and improve archaeological investigation and ultimately tell more meaningful stories about the past.

Further Reading and Contacts

In Scotland, there are a range of expertise and facilities that can assist with geoarchaeological investigation. This includes institution-based researchers, in-house geoarchaeologists at some archaeological consultancy firms, and free-lance or newly qualified geoarchaeologists. In most cases, the first person to contact should be the Local Authority Archaeologist, who will be able to provide advice, as well as an updated list of names and contact numbers for the relevant specialists.

Local Authority Contacts

City of Edinburgh
John Lawson
City of Edinburgh Council
Tel: 0131 558 1040
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Western Scotland
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West of Scotland Archaeology Service
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Email: hugh.mcbrien@wosas.glasgow.gov.uk

Additional Contacts

Scotland's Archaeology Strategy
c/o Heritage Recording and Archaeology Service
Historic Environment Scotland
Tel: 0131 668 8600
Email: ArchaeologyStrategy@hes.scot

Further reading

- Chartered Institute for Archaeologists. Regulations, Standards and Guidance. (multiple documents)

- Historic England. 2011. Environmental Archaeology.

- Historic England. 2015. Geoarchaeology: Using Earth Sciences to Understand the Archaeological Record.

- Historic England. 2020. Deposit Modelling and Archaeology.

- Historic Environment Scotland. 2019. A Guide to Climate Change Impacts.

- Scottish Archaeological Research Framework (ScARF)
  of particular relevance
  - ScARF. 2012. 'Geoarchaeology'.
  - ScARF. 2012. 'Landscape-scale geomorphology and sedimentology'.

- Scottish Regional Research Frameworks (multiple documents)
  of particular relevance
  - PKARF. 2022. 'Geoarchaeology'.

9. Discussion

9.1. Research summary

This thesis focuses on the study of Pictish settlement sites in eastern Scotland through three interrelated topics: preservation and heritage management, daily life in Pictish society, and geoarchaeological methods and theory. Issues with regional 'blackholes' and the perceived poor survival of structures and occupation deposits has resulted in an increasing disparity between our understanding of the elite systems in which early medieval people operated and the actual nature of their everyday lives. It is almost impossible to understand the extent to which this has shaped the settlement record without first assessing the current preservation of known sites and the factors that have affected their preservation. Understanding the prospective threats these sites face is also vital and feeds directly into the research agendas of cultural heritage management, which are increasingly questioning the value of preservation *in situ*. The primary aims of this thesis were therefore to provide a comprehensive understanding of the site formation processes which created, modified, and continue to affect Pictish sites in Scotland, and to assess the value of multi-method geoarchaeology for developing narratives, improving future research agendas, and informing cultural heritage management. To achieve this, regional preservation assessments and an evaluation of national soil datasets were conducted, as well as multi-method geoarchaeological investigations of three early medieval structures in eastern Scotland. This approach aimed to explain why settlement sites are commonly found in such poor states of preservation, to provide new information on their depositional histories, and to evaluate the most suitable suite of techniques for investigating known or newly discovered early medieval structures.

Each of the four research papers that form the core of this thesis contain a discussion of their individual findings in relation to these issues. This chapter integrates and synthesises the results and conclusions of these papers, and applies them directly to the nine research questions posed in section 1.3. This involves correlating the regional observations on post-depositional processes recorded in the review papers with those identified through the original site-based geochemistry and micromorphology studies, resulting in a multi-scale evaluation of the factors affecting the preservation of Pictish structures. By establishing this present state of the settlement record, and the factors threatening its survival, it is possible to hypothesise how settlement remains are likely to change in the wake of future factors, such as climate change. Wider questions about settlement activity, the use of space, floor maintenance practices and living conditions, particularly in the domestic sphere, will also be addressed, leading to a discussion of methodological best practice for future excavations. The evidence for preservation and domestic activity will then be combined to evaluate the accuracy of current interpretations of the Pictish settlement record, and how the findings of this thesis fit into previously established narratives. Finally, this discussion will end by assessing the need for a wider integration of the geoarchaeological approach in Scottish archaeology and will put forward suggestions for this procedure, providing the final research output (Chapter 8) as an initiation of this trajectory.

9.2. Preservation

i. *What are the major post-depositional processes affecting the Pictish settlement record in eastern Scotland and how do these differ across a range of environmental settings?*

The results of the research presented in this thesis have established that a wide variety of post-depositional processes are affecting the preservation of Pictish settlement sites at the regional, site, and microscale. Modern agriculture and its ancillary activities were found to be the major processes involved in the ongoing degradation of archaeological sites at a regional level (Chapter 4). Episodes of contemporary rebuilding, later reuse, historic cultivation, and urban development were also identified as having played a significant role in site preservation and survival (Chapters 4 and 5). At the microscale, the preservation of archaeological deposits was seen to be actively affected by bioturbation, illuviation, and soil acidity, which lead to the degradation of organic material and the leaching of calcareous components such as wood ash (Chapters 6 and 7; Table 9.1).

Sites in lowland settings were most significantly impacted by agricultural attrition, where effects ranged from the complete truncation and scarring of archaeological deposits to the physical fragmentation and chemical deterioration of artefacts. This is clearly a bias related to environmental setting, as these lands are the most favourable for arable agriculture and have been used in this manner since prehistoric times (Hay et al. 2000; RCAHMS 2007; Wiltshire et al. 2020). The eastern coastal strip that stretches from the English Border up to Inverness now accounts for well over 90% of the present-day arable cropping area of Scotland (Hay et al. 2000: 7). Coastal erosion is another environmentally-specific post-depositional process that can have devastating effects on the survival of sites in the coastal zone (Dawson 2013, 2015; Graham et al. 2017; Hambly 2017). Interpretation at Dunnicaer was significantly impeded by truncation of the structure's wall and occupation deposits, and the scale of early medieval settlement already lost to this process remains unclear. This is especially significant for eastern Scotland, where coastal promontory forts appear to be a particularly important settlement type (Noble 2019a: 46).

Micromorphological analysis revealed significant differences in the survival of early medieval occupation deposits across the three case study sites and indicated that this was intimately linked to the types of soils on which they were situated. Whereas the more organic silty sediments of Lair and Dunnicaer retained evidence of relic microstructures, occupation deposits in the course, free-draining sands of Burghead were almost completely devoid of archaeological detail (Fig. 9.1). The main processes of degradation at Burghead were bioturbation and eluviation; extensive earthworm action had reworked surviving material into microscopic aggregates of organic matter which were subsequently moved down through the soil profile by percolating rainwater and soil fauna. This mirrored the findings of the regional assessment, which identified that sites with sandy soils typically reported more significant impacts of bioturbation due to their loose and more easily penetrable soil structure.

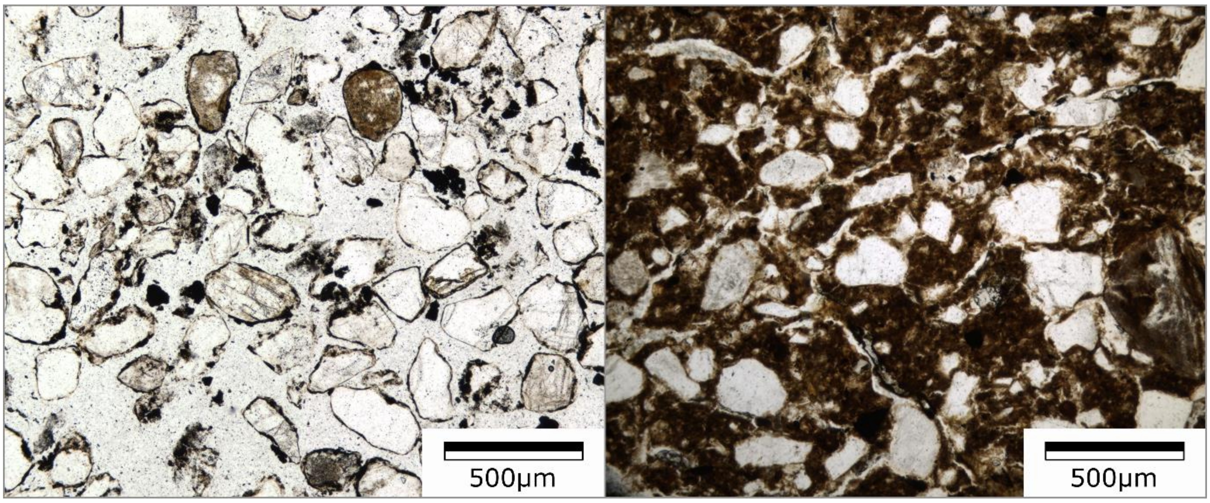

Fig. 9.1. Comparison of microstructures at Burghead (left – BHF16-A, 106) and Dunnicaer (right – DUNC16-A, 1009.2)

Bioturbation was found to have occurred widely across the region. It was recorded in all environmental settings, regardless of topographic location or soil type, and was identified at each of the case study sites. Prior to this thesis, very few investigations of Pictish structures afforded this process any further evaluation and the omission was particularly pronounced in upland environments, where agriculture and site reuse did not provide adequate explanations for the lack of clear occupation deposits. Micromorphological analysis at Lair recognised that soil turnover and channels from earthworms and roots had impacted all sampled areas, but also identified that no microstructure had been completely destroyed by its action. Bioturbation had also not occurred to the same extent across the site; in areas where the microstructure was more compacted (e.g. the byre), earthworm activity had not resulted in the same degree of sediment granulation, demonstrating that preservation potentials were also influenced by the processes and inputs that had formed original archaeological surfaces. Studies have shown that earthworm activity is limited by very low soil pH and it is notable that the upland settlements in both the regional and case study assessments provided the lowest pH values (Tyler et al. 2001). The presence of unusually clear stratigraphic turf sequences at Lair also indicated that, at least in upland settlements, bioturbation was unlikely to be the primary reason for the absence of coherent archaeological stratigraphy in structure interiors.

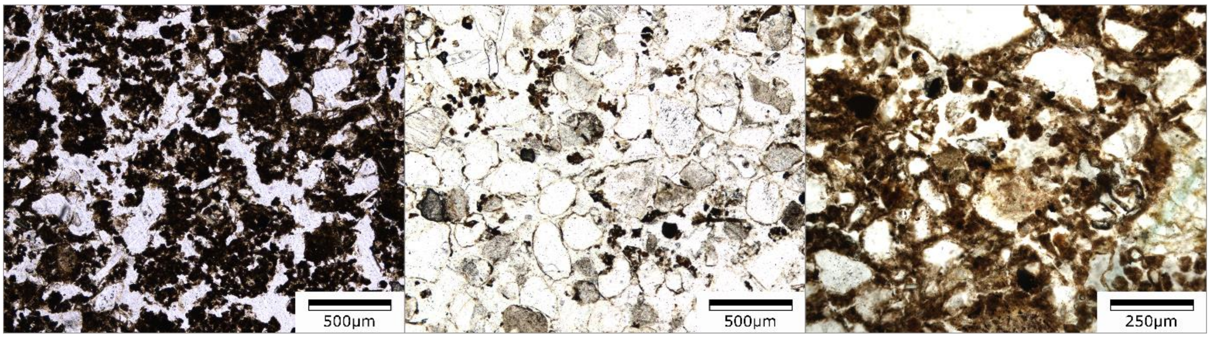

Fig. 9.2. Evidence for bioturbation in case study micrographs (left – channels containing excremental pedofeatures at Lair, GS16-B 220.1; centre – excremental pedofeatures in the form of intergrain microaggregates at Burghead, BHF16-E 106; right – channels containing excremental pedofeatures at Dunnicaer, DUNC16-A 1009.2).

Despite limited empirical investigation at the site level, soil acidity is commonly cited as the reason for the lack of organic material recovered from Pictish settlement. This was supported by the regional preservation assessment, which recorded both the poor preservation of artefacts/ecofacts and widespread acidic conditions in the modern topsoils. The spatial pH and microrefuse assessments at Lair and Dunnicaer provided empirical support for this generalisation, returning median pH values of 3.6 and 4.7 respectively, alongside very few microartefacts other than burnt bone and charcoal, which tend to survive well in acidic conditions (Table 9.1; Appendix 2). However, there are important exceptions. At Burghead, geochemical analysis returned a median value of pH 7.1 for the upper surface and pH 7.0 for the lower surface, indicating that conditions were neutral rather than acidic. The lack of bone recovered from the site may therefore be more intimately linked to the eluviation process, where the dissolution of carbonates was accelerated by wet and free-draining soil conditions, but it is equally likely that this area of the structure originally contained very few bones, teeth, or shell at the time of abandonment. Investigations elsewhere on the site have recovered large quantities of well-preserved shell and animal bone in midden deposits (Gordon Noble pers. comm.), possibly creating microenvironments that are more favourable to bone preservation (Fig. 9.3).

Fig. 9.3. Well-preserved scapula in the lower citadel workshop area of Burghead fort

In sites with a soil pH of <7, gradual leaching and acidification can change the thickness, colour, and preservation conditions of the sediment left behind (Holliday 2004: 289). However, the micromorphological evidence from Lair and Dunnicaer do not suggest that this was a major factor in determining stratigraphic integrity. Instead, the evidence points towards poorly defined occupational sequences that have resulted from cultural processes, such as floor coverings, maintenance practices, or rebuilding episodes, and truncated and/or shallow deposits have subsequently been subjected to biological oxidation and reworking by soil fauna.

i. *What are the major risks to Pictish settlement sites now and in the future?*

Given this improved understanding of the factors affecting preservation, it is possible to predict how settlement sites are likely to be impacted in the coming years and decades. Ongoing cultivation is clearly a major concern, and the results of this thesis support previous dedicated studies on the management of archaeology within arable zones, which identified that sites located on sandy soils are preferentially affected by agricultural practices (Dunwell and Ralston 2008b). In these cases, the deepening of A horizons by cultivation is accompanied by localised soil erosion that effectively brings archaeology closer to the plough. Current scheduling practices allow ploughing to occur at a consistent depth even when ploughsoil thinning is observed (UK Government 1996), thus sites at risk of accelerated degradation include Newbarns, Hawkhill (Angus) and Kinneddar. Where sites are located on less sandy soils, soil

Table 9.1. Summary of site formation processes recognised through integrated geoarchaeological methods across the three case study sites

Process Type	Sub-type	Site	Features	Interpretation
Anthropogenic	Deposition	All	Differential geochemical and element signatures; layering; differential microstructures, course/fine ratios and inclusions	Intentional introduction and movement of materials through processes including construction, maintenance and dumping.
	Reuse	Dunnicaer	Removal and truncation of lower stratigraphy; deposition of material	Rebuilding episode associated with construction of new hearth.
	Maintenance	All	Shallow occupation deposits; few artefacts or microartefacts; distribution of ash residues within house interiors (charcoal, burnt bone, magnetic mineral signatures)	Suggestive of repeated removal or covering of floor layers and cleaning of houses prior to abandonment. Spreading of hearth ash as floor maintenance practice.
	Animal keeping	Lair	Enrichment of Mn, Zn and organic matter content alongside other common habitation indicators; presence of seeds and charred plant matter	Suggestive of repeated input of animal urine and excreta, plus deposition of animal feed, bedding etc.
	Trampling	Dunnicaer, Lair	Planar void formation, horizontal orientation of microcharcoal and minerals, sediment compaction; fragmentation of calcined bone	Suggestive of direct and repeated animal or human trampling on deposits.
	Rubification	Lair	Reddening of soils and their sediment components	Direct and high-intensity heating of soils and sediment components. Suggestive of isolated burning event. Can be natural or anthropogenic.

Natural	Soil formation	All	Bioturbation; fungal sclerotia; granulation of groundmass; root voids	Weathering and reworking of archaeological and natural sediment horizons by soil fauna and vegetal growth.
	Soil acidity	Dunnicaer, Lair	Low pH value (< 5.5); relative absence and/or chemical weathering of bone and organic matter*	Chemical deterioration of organic and mineral components.
	Bioturbation	All	Sediment granulation; faunal channels and root voids; horizontal and vertical displacement of material; excremental pedofeatures; biological and manual degradation of plant material	Disruption and destruction of archaeological material by soil fauna and vegetal growth.
	Eluviation	Burghead, Lair	Enaulic and chitonic microstructure; gradual decrease of microaggregate concentration down soil profile; comparative elemental signatures in upper and lower layers; Fe mineralisation	Downwards movement of fine organic material and soluble elements through sediment profiles. Suggestive of high degree of water percolation, free-draining deposits, and disturbed upper horizons.
	Diagenesis	All	Chemical weathering of bone, organic matter, and wood ash	Suggestive of free-draining sediments, oxidising conditions, and acidic soils.
	Element retention	Dunnicaer**	Correlation between Cu, Ca and Sr concentrations and highest distribution of bone	Suggestive of retention and possible uptake of certain elements.
	Mineralisation	Dunnicaer, Lair	Fe/Mn and calcium phosphate formation as minerals (formation of nodules and intercalations) or crystals; plant pseudomorph formation	Suggestive of periodically waterlogged or saturated conditions.

* Absence of bones not solely attributable to low soil pH; likely to be a combination of diagenetic and anthropogenic processes (as hypothesised for Burghead)
** Likely to also be present at Burghead and Lair but not directly identified

compaction is a more significant threat that has the same impact of bringing archaeology closer to the zone of erasure. Compaction often requires deep and invasive remedial operations, such as subsoiling or pan-busting, which can result in the complete destruction of archaeological material (Oxford Archaeology 2002: 6–7).

Another consideration is the extent to which land use is likely to change over the coming decades. At the time of writing this chapter, the world has just welcomed its eight billionth person, and predictions indicate that this will increase to 9.7 billion by the year 2050, resulting in a global need for 60-100% increase in food production (United Nations 2022). Scotland is poised to increase its agricultural capacity (AIC Scotland 2019) and whether this translates into land use conversion and an increase in agricultural land remains to be seen. The effects of agriculture on the archaeological record have already been established, and should its area of impact spread, or practices become more intensive, we face the prospect of further loss within these environments. The number of households in Scotland is also projected to increase, rising 5% from 2.48 million in 2018 to 2.60 million in 2028, and by 10% to 2.71 million in 2043 (National Records of Scotland 2020). The potential for new development-led discoveries – and their destruction – is therefore significant.

Yet the clearest threat to the preservation of archaeological heritage are changes resulting from climate change. Future climate predictions are damning and are expected to drastically alter the preservation potential of soils and sediments in Scotland and elsewhere in the coming years and decades. For eastern Scotland, the combination of hotter, drier summers and increased winter precipitation will likely have the most damaging effect. Rates of bioturbation are expected to increase due to longer growing seasons that encourage the spread of new and invasive species, and deeper and more penetrative root growth (SAC 2007; Harkin et al. 2019: 33). Waterborne soil erosion and soil compaction are exacerbated by wet conditions and are likely to become a more significant problem as Scotland is subjected to wetter autumns/winters, and more frequent and extreme rainfall events (Troldborg et al. 2013; Lilly et al. 2018: 13). In general, sites located on sandy soils appear to be particularly at risk of future change, given their increased susceptibility to agricultural attrition, soil erosion, bioturbation, and eluviation (Chapters 4 and 5; see also Dunwell and Ralston 2008b). Soils which are seasonally wet, but dry in the summer, also provide the poorest conditions for the preservation of organic matter, as the cycling of soil moisture levels encourages ‘flushes’ of more intense microbial activity (Kibblewhite et al. 2015: 250; Martens et al. 2016). Increased concentrations of atmospheric carbon dioxide have already been linked to greater microbial activity and the potential to recover any surviving organic deposits, structural elements, or artefacts, even at the microscale, is quickly waning (EEA 2012). Activities that disturb the soil and re-distribute soil organic matter are also likely to accelerate aerobic degradation in archaeological sites (Kibblewhite et al. 2015: 250). Tillage is the most obvious contributor to this process; however, archaeological excavations can be seen to perform the same action at a smaller, but significantly more targeted, scale.

Strip-and-map excavation methods, such as those conducted at Rhynie and Portmahomack, have significantly improved the understanding of the Pictish archaeological record, particularly in comparison to the more limited results achieved through keyhole strategies (Chapter 2) (Carver 2012, 2016; Noble et al. 2019b). Yet the impact of these excavation techniques on exposed archaeological material has not yet been established. Part of the issue lies in the fact that cultural heritage management in Scotland continues to encourage the preservation of archaeology *in situ* and assumes that, by simply reburying the archaeology, it will be preserved in the best possible condition (Scottish Government 2011). The inaccuracy of these principles has already been demonstrated in Norway, in areas where burial conditions provide a suitable analogue for eastern Scotland (Martens 2016; see also Martens and Bergersen 2015; Martens et al. 2016). It was found that not only are these sites affected by climate change, but since many sites are situated in areas with modern activities such as agriculture, urban development, and archaeological exposure and excavation in advance of development, their conditions are constantly changing and their scientific potential becomes reduced through gradual degradation (Martens 2016: 92). Accompanying this is the fact that many of the structures exposed by strip-and-map methods are then not investigated in any detail beyond field investigation (often only in the form of half-sections or slot trenches through negative features) and occasional soil sampling. The three structures analysed in this thesis are the first high-resolution geoarchaeological investigations in eastern Pictland but are by no means representative of the area's diversity in structural form or environmental setting. Archaeology is a finite resource and if land use is set to change and rates of degradation increase, it is important that we recognise the potential impact of excavation strategies and approach each of these sites with the most suitable suite of techniques in order to extract as much information as possible before it is lost or further degraded.

9.3. Domestic activity

iv. *Do poorly preserved structures and occupation surfaces retain information relating to site formation and the use of space?*

v. *If information about site formation and the use of space can be found in occupation surfaces, what significance does this have for the interpretation of early medieval life and society?*

The application of multiple overlapping geoarchaeological datasets and geostatistical analyses conducted in this thesis enabled a more detailed and nuanced interpretation of early medieval structures than has previously been achieved in eastern Scotland. This was most apparent at Lair (Chapter 6), where the larger sampled area revealed a seemingly 'invisible floor', producing clear patterning in the data that provided new perspectives and permitted a refinement of existing hypotheses and interpretations. This included confirming that the annexe had functioned as a workshop, and that animals were stalled in the eastern end of the structure, as well as identifying physical and cognitive partitions of space. The turf walls also revealed new evidence for construction decisions and/or phasing at the site, demonstrating that evidence for domestic activity was not confined solely to interior occupation deposits. The studies at both Burghead and Dunnicaer (Chapter 7) similarly enhanced our understanding of the sites, though their overall interpretability was lessened by their more truncated structural elements and smaller excavation areas, which failed to capture significant deposits such as turf walls (Dunnicaer) or internal features (Burghead). Nevertheless, their analysis helped clarify the outline and dimensions of the fragmented structure at Burghead, and provided new layers of detail, including wattle-and-daub construction, partitioning of space, interior remodelling, and the use of dung as a potential fuel source. Thus these studies have confirmed that poorly preserved occupation deposits and fragmented structures *do* retain information related to early medieval domestic activity, and that this information can provide important new insights, even when floors were not preserved well enough to be clearly defined in the field or in thin-section.

Elemental evidence of animals in the byre at Lair provides empirical support to the hypothesis that humans and animals co-habited in Pitcarmick-type buildings (Alcock 2003: 263–264; Carver et al. 2012; Strachan et al. 2019). The construction of a byre-house signifies a sociality with nature that can now be studied at a local and architectural level and offers a foundation from which we can interpret human-animal relations and launch new research questions regarding living conditions, health, and the spread of zoonotic diseases (Nisly 2019). The survival of micro-residues in occupation deposits also allows us to ‘read’ and understand early medieval domestic and industrial/craft activities within an environment that both humans and animals respected, and indicates that techniques such as faecal biomarker and sedimentary aDNA analysis may be successful in developing these narratives (Anderson et al. 2017: 399; Harrault et al. 2019; Nisly 2019). The potential variety of fuel sources recognised at Dunnicaer, which included wood and dung, also introduces a sociopolitical component. If the occupants were indeed sourcing dung for fuel, where were these animals kept and where were their products being processed and dried? Given the relatively small area of the promontory it seems unlikely that all processing activities were conducted in the fort interior. If this is the case, where was the offsite location? Was management of the livestock delegated to an offsite rural settlement through a system of land holding, or was it more intimately linked with the fort and conducted by its occupants?

The findings at Dunnicaer and Burghead appear to confirm the hypothesis that forts had significant residential elements (Noble and Evans 2022: 62–64). The overlying hearths, deep floor sequences, and rebuilding episodes at Dunnicaer would also suggest this was in the form of permanent rather than temporary occupation. Interestingly, there was no evidence in the microrefuse or geoarchaeological evidence to indicate the status of the residents or the roles they may have played within the settlement. Both structures produced very few artefacts in comparison to the building at Lair (Chapter 6; see Strachan et al. 2019), mirroring the findings from other enclosed settlement in eastern Scotland (Chapter 2, section 2.4.1). However, the sample size is admittedly small, and whether this indicates different cultural practices and domestic configurations between rural and fortified settings, or simply just more intense maintenance practices prior to abandonment, remains unclear. At present, there is little evidence at the site and microscale to recognise differences in status based solely on structural evidence and their internal deposits.

Floor maintenance practices, indicated by the spreading of hearth ash and removal of cumulative floor layers, present a significant challenge for field interpretation of the Pictish settlement record. Despite the fact that geochemistry could detect and map floor treatment at Lair, there was no detail on the frequency with which ash-spreading events occurred, resulting in a very shallow occupation sequence that proved difficult to identify, trace, or differentiate during excavation. There was also no evidence for microstratigraphy or the linear phytolith arrangements that often occur when organic floor coverings are laid, or animal bedding deposited (Shahack-Gross et al. 2005; Cabanes et al. 2010; Macphail and Goldberg 2018). Whilst an absence of evidence is always more problematic to interpret, the identification of maintenance practices that remove material suggests that buildings are likely to have been in use for much longer than is inferred from the thinness of their occupation deposits in the field. This is most clearly demonstrated at Dunnicaer, where the deposit associated with the well-used lower hearth was noticeably thinner than the cumulative lenses associated with the abandoned upper hearth.

The physical partitioning of interior space was indicated by an accumulation of material at the byre/living divide at Lair and was also evidenced at Burghead by the boundaries of an organic floor (visible both in the field and through PCA – PC1) and the presence of a wattle and daub fragment. Divisions of space are key to understanding the function and arrangement of activity areas, which speak to the wider roles of a household and its members (Hamerow 2002: 22). Whilst examples in eastern Pictland are rare, this study provides two examples with significantly different ground plans to aid our understanding of the ways in which residential buildings were constructed and configured. At Lair, the geochemistry confirmed that a relatively small space was afforded to the living area in contrast to the byre, raising the possibility that additional storage was created through a raised platform in the roof space (Fig. 9.4 – Strachan and Sneddon 2019: 112–114). A similar configuration was proposed for the Flögeln longhouses in Germany – in this case specifically associated with the storage of grain (Zimmerman 1992: 137–138). Though this was not recognised at any of the case study sites, each of the structures appear to have been cleared of large artefacts prior to abandonment. In examples where abandonment has not resulted in extensive artefact removal, the potential for elevated storage is important to the interpretation of internal stratigraphy, as it can result in localised mixed assemblages and commingled deposits (such as in the burnt collapse layers at Bornais – see Sharples 2012).

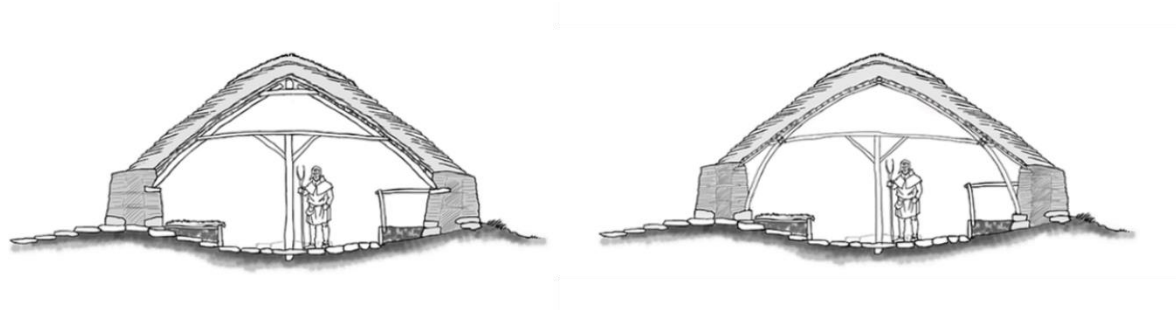

Fig. 9.4. Schematic sections across the Lair Building 3 living area, showing potential configurations of roof and elevated storage space (Mitchell 2018 in Strachan et al. 2019: 114, Fig. 4.5; ©PKHT)

It would certainly appear that internal domestic space in early medieval Scotland commonly had at least one physical partition, and at Lair there was also evidence for the cognitive partitioning of space, including apparent separation of sitting/sleeping areas (associated with 'lighter' domestic activities) from more 'industrial' tool maintenance activities within the context of the living area, suggesting that household interiors were intentionally configured according to the types of activities conducted. Should the database increase, it may become possible to further refine and identify cultural norms in the division and management of residential space.

The subdivision of living areas by walls or screens was recognised at Aðalstræti 16, in Reykjavik, Iceland (Milek and Roberts 2013) and is also evidenced in the continental longhouses of Germany, Denmark and the Netherlands, particularly from the fourth century AD onwards when structures began to grow in length (Hamerow 2002: 23). However, in these latter contexts it has proven difficult to infer the socio-economic aspects of longhouses from their ground-plans alone, owing to their relatively simple structural form and post-depositional truncation (Hamerow 2002: 25). There has also been little evidence to indicate distinctions between public/private, male/female or young/old spaces, despite documentary sources suggesting that such social demarcations did exist during the early medieval period (Hamerow 2002: 25, 38–46). Ephemeral partitions are unlikely to leave diagnostic features in the visible archaeological record, particularly in environmental contexts susceptible to soil turnover, truncation, and attrition (e.g. loose, sandy soils). Without detailed investigation we are therefore likely to miss much of this architectural subtext. The inability to interpret the separated area at Burghead was further affected by the lack of comparative analysis in the north-west hearth end, and possible outdoor occupation surfaces, reflecting the need to conduct these types of investigations across as much of a site as possible. The results of this thesis therefore present a vital development to this area of archaeological discourse. Not only have they proved that these partitions did exist within the early medieval domestic sphere, but they have also provided a methodological protocol that can be applied to any number of comparative examples.

The differences in the composition of the turf used at Lair to construct the main dwelling and the annexe appears to confirm that Building 3 had multiple phases of use, with the most likely architectural scenario being that the annexe was added after the main building had already been established. However, this theory challenges (and is challenged by) previously established phasing at the site, in which a pit deposit within the annexe provided the earliest radiocarbon date for the structure (AD 675–775) and was subsequently interpreted as a foundation deposit (Strachan et al. 2019: 112, 114). Should the annexe indeed be later than the main structure, this would then indicate that the longhouse had been constructed earlier than AD 675–775. An alternative scenario is that the main house and annexe were in fact contemporary, but that the wetter-source (and thus better quality) turves were preferentially used for the construction of the main house. In either case, we can assume that the builders had an intimate understanding of their construction material and recognised these differences in turf composition (Strachan et al. 2019: 130). The differential use of turf may therefore offer insight into the perceived value, and perhaps life expectancy, that the occupants imparted on these structures.

The fact that possible metalworking in the annexe was not reflected in the magnetic susceptibility values in the occupation surface sampled, despite the discovery of whetstones and iron hammerscale in the pits in this room, suggests that the heat-based processing of iron tools occurred elsewhere on the site. Indeed, the lack of a hearth – or any evidence that such a feature had once existed in this structure – precludes its use as a smithy. Ferrous metalworking was in fact not indicated by the microrefuse or geochemical evidence in any of the case study structure interiors, complementing findings from eastern Pictland and elsewhere in early medieval Scotland that indicate these activities took place on settlement peripheries (see Cook 2002; Cook and Dunbar 2008; Woodley 2018). Whilst the presence of sharpening stones at Dunnicaer (Noble et al. 2020: 284), and whetstones and imprinted anvil surfaces on portable stone tools at Lair (Strachan et al. 2019: 84), demonstrate that basic maintenance of iron tools *did* occur at the site, the geoarchaeological findings suggest that primary smithing activities did not occur within the domestic spaces excavated. At this site, and possibly more widely, iron working must have taken place in a distinct space beyond the walls of the archaeologically visible household.

Combined with the results of field, radiocarbon dating, and artefactual evidence, these findings mean that is now possible to begin discussing the biography of Pictish settlement. The aim of geoarchaeology is not to generate large amounts of aimless data – which in fact has proven to have rather an alienating effect (Huisman and van Os 2016; Goldberg and Aldeias 2018) – but to develop a more refined understanding of each site and their unique site formation processes (Wouters 2020: 88). Rather than comparing these results through raw data and quantitative tables, the multi-faceted nature of settlement can be drawn out more easily through a biographical approach (Goldberg and Aldeias 2018; Wouters 2020: 88). To achieve this, each case study site has been afforded a short narrative below:

a) Lair – Building 3

Building 3 was constructed during the seventh century AD within a multi-period landscape when at least two contemporaneous structures were already built and in use (Strachan et al. 2019: 110). The builders sourced good quality saturated turf for the longhouse and made use of the area's even glacial till, constructing the walls and internal surfaces directly onto the natural substrate. By the time of its completion, it stood as the largest and most prominent structure within the settlement. The interior was physically partitioned by a wattle panel, separating the living area in the west from the animal housing in the east. Space in the living area was limited and activity was further divided by a cultural or household behaviour, with more industrial activities taking place in the area between the hearth and the partition wall. Behaviours in cleaning practices also varied between the physically demarcated zones. Floor coverings appear to have been lain and maintained in the living area, while wood ash was removed from the hearth and reused in the byre to absorb moisture and odours.

As the settlement developed, so too did Building 3. The entranceway was remodelled (Strachan et al. 2019: 112) and a multi-functional workshop for butchery and tool maintenance was added to the southwestern wall. Occupation continued until the building was abandoned towards the end of the ninth or early tenth century (Strachan et al. 110). Its internal surfaces were cleared of large artefacts, floor coverings were removed, and the roof appears to have been dismantled. From this point, a palimpsest of processes – organic degradation, root and earthworm activity, sheep trampling and medieval agriculture – impacted the building until its excavation. Its turf walls degraded to form shallow banks and its past remained hidden for over a thousand years. The most recent phase in Building's 3 history has therefore been one of revisiting its stories and attempting to interpret the remains at a site, structural and molecular scale.

b) Burghead – Building 2

Building 2 was constructed during the ninth century AD, towards the end of the early medieval occupancy of Burghead fort. Its construction over the remains of an earlier structure appears to represent a new building rather than remodelling of existing structural elements, perhaps indicating a reconfiguration of the area during this period. The building was divided into two distinct areas – a living area centered around a hearth at the northwest rounded end that was accessed via an entranceway, and an activity surface of unknown function in the southeast. Later in the structure's history, this partition may have been consolidated in wattle-and-daub. Broadly contemporary to this was the establishment of a large exterior pit that respected the northern turf wall. The building appears to have been abandoned at some point in the tenth century and cleared of most artefacts, save for a pierced Anglo-Saxon coin that indicated the occupants had interacted with long-distance trade networks (Gordon Noble pers. comm.).

The site was then left to decay. At least part of the structure was destroyed in a burning event and the turf walls eventually gave way, perhaps taking the roof down with them. Wind-blown sand began to accumulate and the site eventually became hidden through the passage of time. Yet activity was still ongoing. Much of the detail regarding life in Building 2 became fragmented by soil fauna and was distributed downwards through its layers by percolating rainwater. Nearly 900 years later, when occupation returned to the fort, humans again began to alter Building 2. Parts of the structure were truncated by modern walls and waste material was dumped near its southern wall, introducing an entirely different chemical signature that impacted its archaeological layers.

c) **Dunnicaer – lower terrace structure**

The lower terrace structure at Dunnicaer was constructed in the early centuries AD, at what is now considered the beginning of the Pictish period. The ground surface was prepared by depositing loam and angular gravel-sized rocks directly onto the bedrock in order to level the lower terrace hollow and create a suitable occupation surface. Exposed bedrock on the eastern side appears to have been utilised as part of the walling, which was likely constructed in turf. The first phase of occupation included the repeated and long-lived use of a large hearth. Later in its history, associated occupation deposits were removed, the floor was levelled and prepared with fresh turf, and a new smaller hearth was built directly on top of the original. This hearth was the focus of domestic activity that included cooking and heating the residence with wood and animal dung. Once the fires had died down, large fragments of bone were removed and placed to the north of the hearth, whilst the ash was spread across well-trampled floor layers.

The structure was cleared of cultural artefacts and abandoned with the fort sometime in the fifth century AD. The roof appears to have been removed and midden deposits of organic-rich soil with charcoal and fragments of animal bone were dumped over its interior (Noble et al. 2020: 284). Material from the upper terrace then slumped downwards, covering the structure and burying its layers. This slump not only preserved the structure's stratigraphy but also protected it from cultivation in the nineteenth century that destroyed comparative deposits in the upper terrace. Over time, the promontory was ravaged by coastal erosion, which removed the superstructure of the lower terrace building and our understanding of its extent and form. Soil fauna also acted at a much smaller scale to alter – but not completely destroy – its cultural record.

In pulling together these narratives, we can identify decision making about how domestic spaces were organised and the interplay between different kinds of place-making. Physical and cognitive partitioning of space was used to define activity zones, both in and outwith the physical walls of the primary residential structure. The lack of evidence for metalworking or fuel storage suggests that the home was not the sole nucleus of domestic activity, and indicates intrinsic connections with other structures and activities that formed the *domus*. Naturally, this presents a cognitive and methodological problem for the archaeologist, who is then challenged to identify these more ephemeral settlement areas. The geoarchaeological investigations in this thesis have shown the potential for integrated techniques to be used not only in the investigation of visible structures but also as prospection methods in the absence of architectural remains.

Evidence in the turf walls at Lair appears to confirm that Building 3 had multiple phases of use, providing further evidence that there was a dynamism of form and construction in upland settlement. Combined with the partition of space and maintenance practices, this suggests that Pitcarmick-type buildings were well-planned, highly organised, and well-resourced permanent farms, providing evidence against theories that have proposed temporary or seasonal occupation (e.g. Alcock 2003: 265; Carver 2012: 195). With regards to the life cycle of structures, there is both a permanence and ephemerality reflected in the archaeological evidence. Floor coverings and cleaning practices simultaneously maintained and removed occupation deposits, leaving behind thin and truncated deposits that bely the complex palimpsest of activity which formed the fabric of everyday life. At Dunnicaer, the physical removal of accumulated stratigraphy prior to the construction of a hearth immediately above a well-used predecessor is further testament to the fluidity of settlement, as well as a dichotomic relationship that seems to both respect and obscure the past.

No site is impervious to the processes of time and even permanent structures can fall into archaeological invisibility. Each site displayed its own unique palimpsest of post-depositional events that extended from the moment of site abandonment to the present day. Though we can discuss the occurrence of these processes on a generalised regional scale (Chapter 4), actually understanding how they impact a site requires a more comprehensive assessment of site biography and its environmental context. Geoarchaeology has proven fundamental to both and has refined not only the scale at which these sites are understood, but also their anthropogenic and natural changes through time.

9.4. Methods

vi. To what extent can national datasets on land use, soil conditions and erosion modelling be used to provide remote localised information on the preservation environment and predict post-depositional events and prospective threats to a region's archaeological resource?

The relatively high degree of correspondence between site-based observations and the results of land use, soil acidity, and soil description datasets presented in Chapter 4 offers the initial impression that freely available resources can be used to predict preservation factors and their impacts. As the datasets present modern values, their application would be best suited to remote assessments of current or projected risk, which could include scheduling applications, monument monitoring, conservation efforts, identifying candidates for rescue excavation or identifying well-preserved examples for high-resolution excavation and sampling projects. The land cover map (LCM2015) returned the highest similarity rating and is arguably the most valuable dataset for analysis in Scotland, as the synonymity between land cover and land use permits an evaluation of the different levels of threat or protection afforded to archaeological remains.

However, this is somewhat misleading, given the lack of supporting information at the site-level regarding the impact of different land and vegetation covers on archaeological monuments (e.g. the impact of heather cover and associated burning practices), and few assessments of soil acidity. The median pH values at Lair and Dunnicaer proved similar to those in the topsoil dataset, however the values returned for Burghead (pH 7.1 and 7.0) contradicted the generalised data, which had indicated that the site was weakly acidic (pH 5.7). Based solely on the national dataset value, the lack of bone recovered from the site could be interpreted as resulting from dissolution in an acidic environment, whereas the reality appears more nuanced (section 9.2). The lack of national soil data relating to important post-depositional processes, such as bioturbation and fluctuating groundwater, also means that remote assessment can only offer information on certain aspects of the preservation environment. Perhaps most significant was the discovery that neither of the coastal models provided a suitable reflection of erosion events and would have vastly underestimated their current and prospective threat. These findings mirror the conclusion of Fenger-Nielsen et al.'s (2020) study, which stated that the usability of generalised datasets for archaeological purposes must be improved through detailed site-based knowledge of different environmental conditions and their processes of degradation (Chapter 3, section 3.1.1).

vii. *What is the most suitable suite of geoarchaeological and statistical techniques for investigating fragmentary buildings and occupation surfaces?*

The findings in this thesis mirror those of previous studies that have shown that the most effective way to detect and interpret activity areas on archaeological sites is to integrate as many complementary geoarchaeological methods as possible (e.g. Jones et al. 2010; Shillito 2017; Gardner 2018; Kidder et al. 2021; Reidsma et al. 2021). Each individual method provided a unique set of data and by combining field observations with geochemical analysis, micromorphology, and statistical analyses, it was possible to identify patterns, support hypotheses, and present new detail about site use. It was also possible to use these methods to assess site preservation and the impact that preservation conditions had on the formation of spatial datasets. Most importantly, these methods were effective even when sites were highly truncated or degraded.

Methodologically, this study has built on previous research (Sharples 2012; Milek and Roberts 2013 – Chapter 3, section 3.1.4) by integrating multivariate statistical analysis in the high-resolution spatial assessment of structure interiors. PCA proved to be highly effective in detecting and reflecting activity areas, particularly when mapped across the interior space. At Lair, it was critical in identifying the partitioning of space and the different uses of spaces within Building 3, while at Burghead it clearly defined the building's shape in the absence of structural remains. However, PCA could not be used at Dunnicaer due to its small sample size, which has implications for future studies that may attempt highly integrated techniques over a small sampling area. A notable point of deviation with previous studies was that micromorphology was not able to add great detail to the identification of activity areas. This was due to the thin, truncated or eluviated nature of the occupation deposits, which stand in stark contrast to the well-preserved, microlaminated deposits typically targeted for archaeological reconstructions (e.g. Shahack-Gross et al. 2005; Shillito 2017; Borderie et al. 2020; Robertson and Roy 2021; Grono et al. 2022). Thus a reliance on the techniques and approaches utilised on well-preserved sites may not always be applicable to more ephemeral deposits or sites in more advanced states of degradation. In the three case studies presented here, the integration of complementary techniques *spatially* proved far more effective in sites where deposits were hard to identify in the field or recognise in profile.

That being said, such highly integrated approaches are time-consuming and often beyond most excavation budgets, particularly if the areas are large or sampled at a high resolution. The results of this thesis have helped refine the methods that most complement one another, particularly when identifying issues of preservation biases, such as the microrefuse survival at Lair, bone presence/absence at Burghead, and element retention at Dunnicaer. Thus there are certain techniques that should be conducted collectively when systematically sampling and analysing soils and sediments for activity area analysis and/or preservation:

1. Artefact assemblages and their distribution patterning should be supported by soil pH and soluble salt concentrations (electrical conductivity) to understand preservation conditions and detect variations at the microscale.

2. Organic matter content can be conducted alone to map relative concentrations across a site, but is well-suited to integration with pH, electrical conductivity, and multi-element analysis.

3. Magnetic susceptibility can be conducted alone to map relative values across a site, but is well-suited to integration with microrefuse analysis.

4. Multi-element analysis should be complemented by microrefuse mapping (charcoal and bone) to assess the degree to which elemental trapping has occurred, and pH analysis to assess chemical processes such as bioavailability and vulnerability to leaching.

5. Multi-element analysis and any corroborating geochemical assessments should be analysed with multivariate statistics (e.g. principal component analysis) to identify relationships between variables and increase interpretability. Mapping these results across occupation surfaces will also aid the identification of activity areas and the division of space.

6. Micromorphology should underpin any assessment of activity areas and/or site preservation. Though it appears to provide little indication of differentiated activity zones in poorly-preserved occupation surfaces, it is by far the most powerful analytical tool in identifying post-depositional processes and evaluating stratigraphic integrity.

A final point is that, even when occupation deposits appear to be in good condition, micromorphological analysis should still be conducted to assess their integrity. The Burghead occupation deposits were believed to offer a rare example of favourable preservation, given their fortuitous survival under wind-blown sand and modern overburden, and it was for this reason that they were initially identified as a suitable candidate for high-resolution geoarchaeological analysis (Noble and Evans 2022: 63). However, the contradiction between this field observation and the micromorphological assessment is striking. The extreme post-depositional transformations (bioturbation and illuviation) recognised in thin-section show that field assessment of stratigraphic preservation can be misleading and underlines the need for preservation assessments to be conducted at each individual site. This is particularly true if similar deposits are assumed to represent favourable preservation and subsequently used for activity area analysis (e.g. the floor deposit subjected to phytolith and diatom analysis at Cairnmore – see Prado and Noble 2022; Chapter 2, section 2.6. this thesis).

9.5. Revisiting the settlement record

ii. To what extent have major preservation factors influenced our interpretation of the Pictish settlement record?

Chapter 2 outlined the theoretical and methodological factors that have contributed to the idea of eastern Scotland as a *terra incognita* (section 2.8) and demonstrated the most widely held hypotheses regarding the limited identification of Pictish sites and our poor understanding of everyday life. It is now possible to further refine these interpretations and reflect on how preservation factors have framed our thinking.

It is clear that the remains of turf and timber structures have indeed survived poorly in the ground and that this is particularly pronounced in sandy soils. Case study evidence that sandy deposits are preferentially susceptible to physical attrition and biological degradation helps explain the lack of buildings recovered in agricultural areas where such conditions prevail. If rural structures were primarily built from turf with few earthfast elements, then it stands to reason that the majority of upstanding evidence has now been largely destroyed through intensive modern cultivation (Noble and Evans 2022: 59). However, this does not exclude the potential for new discoveries in lowland arable contexts. The scooped structures at Easter Kinnear are proof of rural settlement survival and approximately half of known Pitcarmick-type buildings contain sunken floors similar to the byre at Lair (RCAHMS 1990: 12; Strachan et al. 2019: 128). The study at Lair has proven that floors can survive within these structures and the potential for their discovery and analysis beneath the ploughsoil could rewrite our understanding of rural settlement survival and location. However, this presents the particularly difficult challenge of identifying partial cropmark features through aerial photography (Strachan et al. 2019: 124). A review of oblique aerial photographs in 2012 indicated at least 200 possible examples in eastern Scotland, and though it is highly unlikely that all will be early medieval in date, there is certainly enough evidence to suggest that Pitcarmick-type monuments can be identified in lowland contexts (Strachan et al. 2019: 124). Thus, the topographic bias that has resulted in a relative dearth of rural lowland sites but favoured survival and recognition in upland environments can only to a certain degree be explained by preservation factors. There appears to be a substantial component that requires us to readdress where and how we look for new evidence of early medieval settlement.

A related point is the extent to which the record has also been shaped by patterns of reuse. A major problem of identifying sites in arable contexts is that prime settlement locations are likely to have been in almost continuous occupation (RCAHMS 2007: 245). Chapter 4 identified that reuse of buildings was common on Pictish settlement, whilst Chapter 5 raised the idea that this could lead to the masking of remains. Sites such as Carn Dubh, Lair, Pitcarmick, and Tap o'Noth have all demonstrated this reality (Chapter 2) and again were found above the altitudinal limits of intensive agriculture. The relative dearth of lowland settlement is therefore likely to be related to cultural patterns in the location and reuse of settlement.

The loss of organic and artefactual material in Scotland's acidic soils has been well substantiated throughout this thesis and appears to provide a suitable explanation for the limited artefact and ecofact assemblages recovered from Pictish settlement sites. Certainly, at Lair, high soil acidity provided a clear explanation as to why only calcined bone was recovered and why organic artefacts and unburnt bone were completely absent in the > 2 mm bulk sediment fraction. However, buildings also appear to have been kept very tidy and their floors subjected to regular maintenance that removed the vast majority of deposits and cultural artefacts. Thus the limited or absent stratigraphy reported on the majority of Pictish settlement appears to be the product of both natural factors and cultural activity. Maintenance practices are part of the fabric of daily life and this thesis has proven that it is a misnomer to equate thin or homogenous stratigraphy with an absence of evidence for settlement activity. Pictish occupation deposits do indeed retain evidence of settlement life – we just need to approach them with the correct research strategies.

9.6. Integrating geoarchaeology

viii. How can geoarchaeology contribute to cultural heritage management strategies?

This thesis has provided an original contribution of knowledge that has important implications not only for the interpretation of cultural activity but also its cultural heritage management. Furthermore, this applies not just to Pictish sites, but a large number of sites from all periods. Climate change has triggered a review of *in situ* preservation strategies (see Harkin et al. 2019) that requires heritage managers to be able to estimate the current and projected risk faced by specific archaeological sites. The methods outlined in this thesis have offered one means of considering preservation and risk and indicated the potential of national data on land use, soil acidity and soil description to inform management strategies (Chapter 4). However, they have also emphasised the need for site-based geoarchaeological data to fine-tune generalised models and datasets. Whilst the case studies were conducted at a high resolution, accessing preservation data for heritage management strategies does not require a considerable workload or the need to expose a significant proportion of the site. Meaningful data on soil and sediment properties can be gathered from an exposed section, small test-pit or core, and analysed using detailed recording methods and any combination of the techniques outlined in Chapter 8. Historic Environment Scotland have noted that their current monitoring practice for scheduled monuments underestimates the threat to sites located beneath the ploughsoil and does not produce data that can be combined or compared against other monument types (Historic Environment Scotland 2018). Combined desk- and site-based geoarchaeological work could therefore provide empirical and semi-quantitative data without the need for wholly intrusive excavations.

Historic Environment Scotland has also acknowledged that its understanding of the construction and degradation of upstanding turf and earth monuments is significantly behind that of stone and mortar constructions (Lisa Brown pers. comm.). Scotland contains a large number of monuments that are either formed from turf, earth and peat, or are situated on and protected by turf. This includes broad monument types such as burnt mounds, field boundaries and turf buildings, as well as Properties in Care such as Maeshowe chambered cairn, the Antonine Wall, and the Lewis blackhouses, all of which that form a core part of Scotland's publicly-accessible heritage commodities. The Lair study has demonstrated the ability of geoarchaeology to draw out significant detail regarding turf composition and is primed to aid in assessments of their preservation or create more detailed, nuanced, and reliable narratives of their formation (see also Walker 2006; Gardner 2018). When combined with decay studies, this could also help to predict the impact of climate change and aid the management of some of our nation's most iconic heritage sites.

Additional soil properties not assessed in this thesis – soil temperature, redox potential, and soil moisture – can be measured through the use of long-term monitoring equipment that is inserted into exposed archaeological deposits. Their trial in unsaturated deposits in Norway found that it was possible to observe the degradation of archaeological material *in situ*, indicating that similar projects could provide key reference detail for archaeological sites in Scotland (Martens and Bergersen 2015; Martens 2016; Martens et al. 2016). However, prominent researchers have argued that this type of monitoring is only effective in preventing *in situ* destruction when the changes to an environment are clearly recognisable and take place relatively quickly (for example, shallow sites in recently drained wetlands) (Huisman and van Os 2016: 378). They also argue that there is often little need for archaeologists to engage in complex monitoring technology or large datasets and that, in reality, these are likely to discourage engagement with such assessments (Huisman and van Os 2016: 374). Instead, the use of low-tech field observations and information gathered at the point of excavation, without the need for specialists, is likely to offer more uptake and success in the future.

It is for this reason that the HES geoarchaeology guidelines form a fundamental part of this research project and its outputs (Chapter 8). The creation of research-led guidelines specifically directed at a non-specialist audience was intended to counteract the perception of geoarchaeology as a wholly specialist discipline, encourage wider engagement with its techniques, improve the quality and collection of data, and place this agency within the hands of the excavators and research directors. Specialist disciplines such as zooarchaeology and archaeobotany are now common requirements of post-excavation archaeological investigation, but these conditions have not been extended to geoarchaeology. This is a particularly significant omission considering that geoarchaeological enquiry can be conducted in the field, often without the need for additional expenses, time, or equipment.

Finally, it was the initial intention of this thesis to assess the impact of site reburial following excavation. Unfortunately, plans to conduct these evaluations were impeded by the Covid-19 pandemic and were no longer feasible in the remaining timeframe. A procedure for how this was to be conducted on a Scheduled Monument is presented in Appendix 4 and provides a methodological strategy from which additional heritage assessment programmes could be launched.

viii. How can geoarchaeological investigation be implemented more widely in Scottish archaeology?

Geoarchaeology suffers an unfortunate reputation as a specialist field that relies heavily on expert knowledge and unintelligible jargon. However, the reality is that geoarchaeology encompasses a wide range of techniques from the most basic field assessments right through to complex biomolecular technology, and can be scaled according to budgets, abilities, and research questions. The most practical way to integrate geoarchaeology more widely is through heritage legislation that requires it be written into the brief of any new research or development-led excavation. In the absence of any formal act, we must be able to demonstrate the value of geoarchaeology to both the archaeologists conducting the research and the end-users who drive its outputs. Chapter 8 was developed with this latter goal in mind. The aim was to create an accessible document that empowers the archaeological community by improving awareness of the scope and techniques of geoarchaeology, whilst simultaneously providing practical guidance on how to collect data with, and most importantly without, the need for on-site specialists.

There is also opportunity for geoarchaeology to be integrated outwith the archaeological sector. The primary driver for this is climate change and recognition that changing soil health will have a profound impact on human health, natural heritage, tangible heritage, land use and agriculture, among numerous other economic, social, and cultural sectors. For example, geoarchaeology could develop a reflexive relationship with the agricultural sector, contributing location-specific soil information which can support the precision management of soil health whilst gaining access to archaeological sites in lowland arable zones. Such an approach would benefit both parties but requires significantly better interdisciplinary communication than currently exists. The biggest barrier facing integrated soil studies is the compartmentalisation of soil research; nature is not an engineered system and cannot be easily fragmented into separate constituents. There is a desperate need to adopt a 'systems approach' that focuses on soil health as a whole, rather than the sum of its individual parts (Vogel et al. 2018; Turner 2021; Harris et al. 2022; Löbmann et al. 2022; Moller and Doherty 2022). Such an approach requires new levels of multidisciplinary collaboration and a multi-scale approach that places a high demand on real time data. Archaeologists are putting new holes in the ground every day and each one is an opportunity to gather information about soil health and preservation conditions. The benefits of geoarchaeological methods and theory extend far beyond the confines of an archaeological structure or feature and there is untapped potential for geoarchaeology to feed into much broader research agendas and become more intimately linked with other soil disciplines.

10. Conclusion

10.1. Heritage at risk

Archaeological sites have the potential to fundamentally change our understanding of the social, political, and cultural spheres of the past. This is particularly true in areas where the known record pertains to a small pool of diverse site types, and the relationships between these site types remain unresolved. The early medieval record in eastern Scotland presents such a setting; our understanding of fortifications and high-status sites have developed rapidly, and new discoveries are increasing the record each year. However, opportunities to study these systems in relation to the daily lives of Pictish people have been limited due to the poor preservation of occupation deposits, regional ‘blackholes’, and a relative paucity of structures in comparison with early medieval England and Ireland. Understanding the processes that have led to this ‘absence of detail’ is therefore crucial in developing reliable interpretations, advancing narratives, and creating appropriate heritage management strategies.

This thesis set out to contribute new information pertinent to these issues by characterising the major post-depositional processes affecting Pictish settlement sites in eastern Scotland. To achieve this, it has examined early medieval settlement evidence at multiple scales and with new levels of detail. At the site scale, qualitative and semi-quantitative examination of past excavation literature was used to obtain a foundational understanding of the range of processes identified during excavations. This was then cross-referenced against national soil datasets to assess whether generalised data were likely to provide a sufficient estimate of risk factors for cultural heritage management. At the microscale, integrated microrefuse, geochemical, geomagnetic and micromorphological analyses were applied to three early medieval structures in order to refine preservation assessments, review the integrity of floor deposits, and evaluate whether they retained evidence of residential activities.

This research has demonstrated that the current Pictish settlement record has been shaped by several key factors. On one hand we have issues of preservation. Modern agriculture and its ancillary activities were found to be the major processes involved in the ongoing degradation of archaeological sites at a regional level, resulting in a relative dearth of identified sites in lowland areas. Known structures appear to have been primarily built from turf with few earthfast elements, and the most logical conclusion is that any upstanding remains have been largely destroyed through intensive modern cultivation within arable zones. At the microscale, the preservation of archaeological deposits was seen to be actively affected by bioturbation, illuviation, and soil acidity, which had reworked stratigraphy to varying degrees and almost completely destroyed occupation deposits in particular contexts. At all scales of analysis, sites located on sandy soils were typically found to have the poorest levels of preservation and appeared to be preferentially affected by these post-depositional processes. Thus settlement sites located on sandy deposits can be considered at the highest risk of physical attrition and biological degradation.

However, it became equally apparent that preservation was not the only factor involved in the creation of this 'absence of evidence'. Topographic biases and difficulties in the identification of sites appear to have, at least in part, resulted from patterns of reuse and the masking of early medieval evidence amongst more prominent settlement remains. This thesis therefore questions a reliance on perceived site typologies and suggests a re-evaluation of how and where we look for settlement evidence. This is likely to include multi-period landscapes and marginal arable zones.

The most significant finding of this research was that occupation deposits retained characteristics of the use of space, even when floors were not preserved well enough to be clearly defined in the field or in thin section. This included contemporary maintenance practices that had removed stratigraphy, resulting in shallow deposits and a truncated depositional history. This challenges previous theoretical approaches to the Pictish settlement record, which have typically interpreted thin or fragmented deposits as a barrier to more detailed understandings of daily life. A historic lack of engagement with geoarchaeological methods can be seen to have perpetuated this mindset. Thus the 'absence of evidence' is also a product of methodological and cognitive issues that have developed from the perceived value of archaeological deposits based solely on their appearance in the field.

The case studies proved that integrated geoarchaeological analysis was successful in identifying activity areas and relating this to maintenance practices, remodelling, the organisation of space, and post-depositional processes. At the rural upland site of Lair, the findings corroborated hypotheses regarding household dynamics and human-animal relations, and provided new perspectives on phasing, off-site activities, and the physical and cognitive partition of space. Information drawn from the turf walls also demonstrated that evidence for domestic activity was not confined solely to interior occupation deposits. This offers a methodological recommendation that structural elements should not be used to constrain archaeological investigations at the microscale. Though survival was significantly poorer at the coastal promontory settlements of Dunnicaer and Burghead, geoarchaeology was able to confirm that the sampled deposits were indeed occupation surfaces, and contributed new information about their composition, spatial patterning, and in the case of Burghead, the spatial extent of the truncated structure. These analyses also fed into broader narratives by providing evidence that forts had residential elements which appeared to be in the form of permanent rather than temporary dwellings.

The discovery of these domestic signatures demonstrates the potential for archaeologically significant material to survive within even the most heavily truncated or degraded Pictish settlement structures. It also shows the role that geoarchaeological methods can play in elucidating their hidden detail and developing the biographies of structures and settlements. However, we are facing the potential loss of scientifically viable remains through ongoing agriculture, changing land use practices, and climate change. Our understanding of how archaeological resources in Scotland respond to changing soil properties is fragmentary at best and predicting the impact of complex changes is almost impossible without a baseline knowledge. Recognition of these issues has already stimulated changes in heritage management strategies (e.g. Harkin et al. 2019) and should similarly encourage a review of the techniques and methods we use to investigate settlement sites.

This thesis has demonstrated that national soil datasets have the potential to predict post-depositional processes and identify risk associated with land use, soil type, and soil acidity. However, many of the relationships between these factors remain poorly explored and there is little understanding of how they relate to different site types or architectural traditions. Results produced at a regional scale therefore need to be refined by site-based preservation assessments and the creation of additional datasets (e.g. redox conditions and soil faunal populations) before they become feasible for heritage management in Scotland. As an isolated technique, micromorphology was by far the most powerful analytical tool in identifying post-depositional processes at the site-level and linking this to states of preservation and stratigraphic integrity. It was also able to provide key detail regarding the anthropogenic modification of sites and bridge the gap between assessments of preservation and site activity. With regard to informing the narrative of daily life, the multiple overlapping datasets and geostatistical analyses produced through this thesis enabled a more detailed and more nuanced interpretation of early medieval structures than has previously been achieved in eastern Scotland. Principal component analysis proved to be highly effective in detecting and reflecting activity areas and was particularly adept at recognising ephemeral divisions of space when results were mapped across the structure interior. Thus this thesis has demonstrated that it is possible to detect and interpretate the possible palimpsest of cultural and natural processes that have formed and altered ephemeral occupation deposits when approached with a robust methodological framework.

Increasing the scope and accuracy of the interpretations posed in this thesis requires active collaboration with soil scientists, heritage managers, academic research directors, and the developer-funded sector. This will ensure that information is collected, shared, and actively utilised. It also relies on each of these sectors being aware of the capabilities of new research methodologies and how to execute best-practice. This thesis has provided several methodological frameworks and case-study examples of how projects may be approached; however, it is the collaboration with Historic Environment Scotland that provides the greatest opportunity to broaden the awareness and appeal of geoarchaeological techniques. The production of geoarchaeological guidelines aimed specifically at a non-specialist audience is intended to reduce the alienation of geoarchaeology as a wholly specialist discipline and encourage a much broader integration with its methods and principles. By studying the very fabric in which people existed, we can collect vital data on the natural and cultural processes that both shaped the lives of past people and threatens the future of their archaeological remains.

The concept of Pictish settlement as ‘heritage as risk’ can therefore be considered on two fronts. The first presents risk in its most obvious sense; climate change and changing land-use strategies pose long-term threats that serve to destroy or degrade archaeological remains. By refining datasets on site preservation, we can approach these issues practically by developing new heritage management strategies that prioritise sites most at risk of destruction or those that have favourable preservation and are likely to retain high-quality evidence. Empirically informed decision-making provides a gateway to policy guidance, and perhaps even legislation, that can solidify these management strategies. The second front relates to the risk of equating poorly preserved sites, or thin and homogenous stratigraphy, with an absence of evidence for settlement activity. This thesis has disproven such a theoretical position within the context of eastern Pictland and presents an opportunity for known sites in a global context to be reassessed, or dedicated geoarchaeological research projects to be developed. Archaeology is a finite resource, and we need to address both of these risks in order to ensure that our current record is understood and managed effectively.

10.2. Directions for future research

Geoarchaeology is highly scalable and the results presented in this thesis could be further refined through the application of additional techniques. The lack of phytoliths observed in thin-section across all sites was puzzling and dedicated phytolith and diatom analysis could help resolve their identification and the reasons for their absence. If used in conjunction with lipid biomarker analysis, this could aid the identification of activity areas and address the hypothesis that floor coverings such as bracken contributed to shallow occupation deposits. Faecal biomarkers in particular could prove effective in identifying the types of animals kept in the byre at Lair and help establish the archaeological signature of their inputs at the site.

The structures studied in this thesis had not been damaged by modern cultivation and so there was little opportunity to assess and compare these impacts at the microscale. A similar study in a lowland arable context (e.g. Cairnmore or Rhynie) could therefore assess the extent to which occupation deposits in these contexts retained micro-residues indicative of past activity. Questions regarding the impact of intrusive archaeological investigation following reburial also need to be addressed and there is significant potential for experimental approaches, long-term monitoring systems, and the resampling of previously excavated monuments. The lack of national data relating to important post-depositional processes, such as bioturbation and fluctuating groundwater, currently means that remote assessment can only offer information on certain aspects of the preservation environment. These are areas primed for new ‘systems approach’ research and integration with wider soil health agendas.

The creation of a database that combines national data with site-based evidence collected from excavations and monitoring efforts could prove highly useful in informing archaeological risk management. The national soil datasets presented in Chapter 3 – coupled with Davidson and Wilson’s (2006) report on potential soil indicators for the preservation of cultural heritage – offer a useful starting point and would help refine many of the outstanding questions and issues identified in this thesis. If geoarchaeological data and descriptions of soils and sediments were more routinely collected (or better yet, written into briefs) during archaeological excavations, this database could be supplemented with real-time, site-based knowledge by practitioners. The HES geoarchaeology guidelines offer practical advice on achieving this without the need for specialised knowledge or equipment. This would result in a dataset that not only indicates risk but actively encourages research into post-depositional processes, the relationships between factors, and how the different aspects of settlement (architectural styles, building materials, longevity of use etc.) can influence these impacts. Such a resource would need to be dynamic and regularly updated as more information is made available about conditions at the site-level.

10.3. Closing statement

It has been a privilege to participate in the excavation and research of some of the most important settlement sites in Pictish archaeology. At all times, this thesis has aimed to improve our understanding of their condition, formation and survival so that this limited resource can be approached in the best manner possible. To continue this trajectory, this work advocates for the integration of geoarchaeological methods and principles not just in early medieval discourse or Scottish archaeology but in everyday archaeological practice. As I sit here writing these final sentences, I think of the wood smoke filling the longhouse at Lair. The cattle settling in the byre, out of sight behind the wattle partition, and the butchery and maintenance activities conducted in the annexe. Because this is where geoarchaeology truly proves itself. In telling the nuanced stories that connect us more meaningfully to past people and their wonderfully fascinating lives.

Appendices

Appendix 1

Tables of Site Formation Processes and their Associated Research Strategies

The following appendix comprises a broad literature review of potential post-depositional processes affecting settlement sites, structures, occupation deposits, and ecofactual/artefactual materials. It also includes the research strategies and methods commonly used in their identification. This was conducted prior to commencing any site-based or regional analyses to provide a reference collection of possible impacts and included, where possible, the identification of Scottish studies and examples as evidence of their impact within comparative environmental settings.

The literature review has been synthesised into tabular format and separated into the following three sections:

- Geological and sedimentary processes
- Biological processes
- Anthropogenic processes

Processes and Impacts	Examples	Research Strategies
Slope processes and colluvial deposits		
Erosion and movement on slopes · Downslope displacement of artefacts and material · Erosion/abrasion of artefacts and features at up- and mid-slope locations · Extent of erosion impacted by underlying geology (soft geology makes sites more vulnerable to erosion) (Goldberg and Macphail 2006: 78-79)	· On the Isle of Lewis, continuous small-scale slumping of the soil matrix, coupled with low-frequency, high magnitude cliff slip events, eroded numerous promontory sites to the point that they now survive as stacks just a few metres across. This is particularly prominent at sites on the till cliffs around north-west Lewis and the conglomerate cliffs of New Red Sandstone on the east coast, due to the relatively soft underlying geology. (Church and Burgess 2003: 61-62)	· Assess landscape setting and geology · Use of detailed field descriptions to identify slope displacement, erosion and sediment type
Colluvial deposition · Poor stratification and sorting of deposits · Inclusion of artefacts from upslope material · Particle size dependent on nature of upslope material · Local preservation of overall integrity and context if whole blocks of sediment are moved *en masse* · Increased stratigraphic resolution downslope as a result of rapid sedimentation · Thickening of deposits downslope · Burial of features at lower slope levels · Possible waterlogging and preservation of organic remains at slope base (potential for formation of iron	· At the Grassmarket, Edinburgh, prehistoric and Anglican features were sealed by colluvial deposits, up to 0.8m deep, that had washed downslope from Castle Rock during the later medieval period. This seal created an anaerobic environment that led to the survival of bone, shell and charcoal fragments which would otherwise have been lost. (McMeekin 2009: 3)	· Use of detailed field descriptions to identify slope profiles and sediment type · Micromorphological analysis to identify dipping bodies of sediment and any inclined alignment of stones and artefacts · Use of geochemical and micromorphological analysis to identify formation of metallic compounds

and manganese pan) (Goldberg and Macphail 2006: 78-79; Historic England 2015: 2-3; Turnbull et al. 2015; Karkanas and Goldberg 2019: 37)		(Bernatchez 2010; Karkanas and Goldberg 2019: 36-37, 40)
Debris flow deposition (mobilisation by water) · No separation of sediment fractions (water and solid material moves together as single semi-plastic body – contrast to other fluvial processes) · Possible incorporation of slope material during movement · Extremely poorly sorted, non-bedded deposit · Elongated deposit characterised by lobate head (snout and lateral deposits) and ridge forms · Lack of internal stratification · Lack of clast segregations (e.g. gravel lenses) · Relatively homogenous fine-grained matrix; courser particles suspended in silty clay matrix · Random to poorly preferred orientation of objects · Debris flows include (but not limited to) the remobilisation of building collapse and other accumulated sediment (Costa, 1988: 116; Coussot and Meunier 1996; Bertran and Texier 1999: 108-109; Mücher et al. 2010: 44-45; Karkanas and Goldberg 2019: 43-47)	· Dating efforts on debris-flows in the Scottish Highlands have identified a correlation between their prevalence and anthropogenic activities, such as burning for forest clearance and pasture improvement. Associating geological activity with archaeological landscapes allows for a greater understanding of human-environment interactions before, during and after these events. (Innes 1983; Ballantyne 1991)	· Use of field descriptions to identify and characterise sediment profiles · Micromorphological analysis to identify lack of lamination and poor sorting of material (Phillips, 2006; Mücher et al. 2010; Pleskot 2015: 128-129; Karkanas and Goldberg 2019: 44-47)
Pauses in deposition · Periods of stability in which no net accumulation of deposits occur · Old surfaces identified through subtle differences in stone content/sorting as a result of surface erosion		· Use of detailed field descriptions to identify sorted stone lines and subtle changes in texture or structure · Micromorphological analysis to identify

· Longer periods identified by accumulation of organic matter (Historic England 2015: 4-5)		discontinuities in sediment profiles · Use of geochemical analysis to assess the degree of soil development
Fluvial processes and alluvial deposits		
Erosion and fluvial action on slopes (by rain/thaw water) · Downslope movement of fine surficial material (transport of pebbles and larger clasts when substrate is super-saturated and slope is steep) · Displacement of artefacts through direct overland flow and erosion of supporting matrix - greater displacement of small, solid artefacts - displacement increases as slope angle increases - little effect on artefacts >20mm when slope <5º · Possible rounding of artefacts (particularly if transported over long distances) · Possible destruction of archaeological sites (high velocity channelised flows capable of destroying standing walls by undermining foundations; minor effect by shallow channelised flows) (Turnbaugh 1978: 597; Karkanas and Goldberg 2019:48-51)	· In 1993, farmland in Fife was subjected to widespread soil erosion when snowmelt-generated runoff was augmented by heavy rainfall. Reports indicated the loss of up to 127m^3 of soil from individual gullies. (Wade and Kirkbride 1998) · In Dumfries and Galloway, a linear feature known as the 'Deil's Dyke' was wrongly interpreted as an artificial earthwork. Exposure of the internal stratification revealed it to be an esker, produced by the natural deposition of gravel and sand in a subglacial tunnel when the last ice-sheet was wasting the valleys of the River Annan. (Jardine 1984: 3)	· Use of field descriptions to assess site integrity and slope environment · Artefactual analysis to assess abrasion
Sheetwash deposition · Thin, lenticular deposit with flat top and weakly erosional base · Lack of clear channelised features · Deposit affected by slope and nature of movement · Steep slope deposits	· In Scotland, there is clear evidence to suggest an association between early prehistoric activity and well-drained glaciofluvial terraces. Examples include Mesolithic pit alignments and the early	· Use of field descriptions to identify fluvial stratigraphy associated with slopes · Micromorphological analysis to assess microsorting, lamination and/or microstructures associated with sheetwash

- movement controlled by saltation, rolling and creep - faint-distinct plane-parallel stratification - poorly sorted · Gentle slope movement - some material moved in suspension - more developed stratification - thin layers (follow pre-existing topography) - medium-well sorted · Potential loss of lamination and free clay particles during high-intensity rainfall (Blikra and Nemec 1998; Bertran and Texier 1999; Nemec and Kazanci 1999; Karkanas and Goldberg 2019: 47-49)	timber Neolithic halls at Balbridie and Warren Field in Aberdeenshire. (Fairweather and Ralston 1993; Murray et al. 2009)	(e.g. loose to dense packed mineral grains or clay-rich aggregates; charcoal or organic laminae; vesicles) (Mücher and De Ploey 1977; Bertran and Texier 1999; Karkanas and Goldberg 2019: 49)
Standing water (including puddles and ponds) · Basin-like substrate with well sorted, fine grained sediments (clay, silt) · Undisturbed planar lamination if body is calm and stagnant · Homogenous sediment if body is turbulent · Bedload sedimentary structures absent · Preservation of artefacts and material if buried by rapid clay sedimentation · Presence and preservation of biological material in large bodies (e.g. charcoal, pollen, phytoliths, macrobotantical remains) · Fine anthropogenic material (e.g. bone, pottery) generally rounded - objects deposited by hand typically lie flat on the depositional surface with random orientation of long axes - objects entered via flash floods or turbulent	· Stratigraphic analysis of deposits in Sculptor's Cave, Moray, revealed a series of fine-grained sands and clays thought to have been formed at a time when the cave was waterlogged. Material artefacts dating to the Bronze Age were largely restricted to an area where a considerable volume of water would have pooled, suggesting they may have been deposited as votive offerings. (Shepherd 2007: 195; Armit et al. 2011: 255)	· Use of field descriptions to identify fluvial stratigraphy associated with standing water · Micromorphological analysis to assess microsorting, lamination and orientation · Micromorphological analysis to identify features and biological material associated with standing water (Pagliai and Stoops 2010: 422-433; Karkanas and Goldberg 2019: 55-57)

action oriented parallel to flow direction · Formation of microscopic sedimentary crusts (microlayers with coarser particles at bottom and finer particles at top; presence of vesicles and planar voids in finer layers) (Pagliai and Stoops 2010: 422-433; Karkanas and Goldberg 2019: 52-57)		
High-energy fluvial processes (including waves and rivers) · Destruction and displacement of archaeological sites · Displacement and mixing of assemblages - greater displacement of small artefacts - displacement of heavy artefacts at high velocities - concentration of artefacts at points of flow disruption (meanders, depressions, obstructions) · Abrasion/rounding of artefacts (can result from long distance transport or water movement over stationary material) · Burial of material if sedimentation rates are high (Brown et al. 2003; Gavrilă et al. 2012; Karkanas and Goldberg 2019: 60-63)	· At Broad Bay, Isle of Lewis, stream-based alluvial action is both eroding and covering numerous sites in sand and mud deposits within the coastal zone, including a probably Norse settlement. (Church and Burgess 2003: 62)	· Use of field descriptions to assess site integrity and alluvial environment · Artefactual analysis to assess abrasion
High-energy deposition · Typically constitute substrate or post-abandonment phases · Specific sedimentary features dependent on alluvial microenvironment (basics described below) · Complex sequences of alternating gravel, sand and clay layers characterised by intercalated beds of various thickness (beach sediments devoid of silt and clay)		· Use of field descriptions to identify fluvial stratigraphy associated with high energy processes · Micromorphological analysis to detect microsorting, lamination, cross-stratification and gravel rounding · Artefactual analysis to assess abrasion

· Massive, very well-sorted and stratified sediments · Individual layers also well-sorted · Grading both internal (i.e. in a layer) and sequential (i.e. sequences of beds each with a finer grain size) · Fine sediments show lamination and cross-stratification · Grounding of gravels, often into elliptical shapes (Nemec and Steel 1984; Goldberg and Holliday 1998; Karkanas and Goldberg 2019: 60-63)		(Angelucci et al. 2013; Karkanas and Goldberg 2019: 60-63)
Aeolian processes and wind-blown deposits		
Aeolian erosion (including deflation) · Abrasion of rock fragments including lithic implements · Formation of ventifacts (facetted and pitted rocks or smooth surfaces with elongated grooves) · Removal of fine interstitial material can result in artefacts from successive deposits being found together in the same 'assemblage' · Horizontal displacement of very light material (e.g. charcoal, seeds, ashes, fish bones) resulting in concentrated assemblages of heavier material (e.g. shellfish, animal bones) (Rick 2002; Goldberg and Macphail 2006: 121-122, 129; Karkanas and Goldberg 2019: 67)	· Over the last 30 years, aeolian deflation of the Barvas machair sands on the western coast of the Isle of Lewis, has exposed huge areas of archaeological landscape, including buildings, human remains, Neolithic monuments and stray finds. This process has been exacerbated by severe rabbit burrowing and high stocking levels, resulting in much of the exposed material being lost to further erosion. (Cowie and MacLeod Rivett 2015: 100)	· Use of field descriptions and artefactual analysis to identify material associated with aeolian processes · Sieving, flotation and artefactual analysis to assess integrity and size-distribution of assemblage
Wind-blown deposition · Burial of sites, features or occupation layers, particularly in coastal locations · Small particles transported over greater distances and periods of time than coarser fractions	· The land surrounding the settlement mound at Old Scatness, Shetland, was found to have been aggraded partly by the addition of fertilisers and partly through	· Use of field descriptions to identify aeolian stratigraphy · Micromorphological analysis to detect microsorting and lamination

· Well sorted deposits of fine to medium-grained sand · Coastal blown sands tend to be better sorted than inland wind-blown deposits · Well-developed horizontal or inclined lamination · Inversely graded microstructure (coarsening upwards) · Alkaline preservation conditions in coastal blown sands (as a result of fragmented shell component) · Deposition of exogenous charcoal (<50µm) (Goldberg and Macphail 2006: 142; Stolt and Lindbo 2010: 376; Historic England 2015: 11)	the deposition of wind-blown sand. (Guttmann et al. 2003: 4)	
Cryoturbation (disturbance by freeze-thaw cycle)		
Repeated freezing and thawing · Changes to original soil structure · Formation of platy microstructures, smooth-walled planar voids and localised compaction · Fine silt suspended in melting water forms capping on lenticular peds · Formation of 'banded fabric' · Granular microstructure in upper part of sediment (area most susceptible to regular freeze-thaw cycle) (van Vliet-Lanoë et al. 1984; van Vliet-Lanoë, 1998, 2010; Milek 2006: 8 Karkanas & Goldberg 2019: 42)	· Excavators at the Palaeolithic site of Howburn Farm, South Lanarkshire, recovered multiple worked flints from depressions in the naturally deposited glacial till. These depressions were filled with glacial meltwater silt, which the flints had penetrated via the process of cryoturbation during the permafrost conditions of the Younger Dryas stadial. (Ward and Saville 2010: 20-21)	· Micromorphological analysis to identify freeze-thaw structures and micro-sorting (Harris and Ellis 1980; van Vliet-Lanoë 1998, 2010; Milek 2006: 84; Karkanas and Goldberg, 2019: 42)

Frost heave · Upwards displacement of artefacts and materials · Extent of displacement dependent on various soil-environment interactions (soil texture, frequency/rate of frost penetration, soil pressure etc.) · Objects with greater surface area and effective height will have greater uplift · Objects buried near the surface will undergo more freeze-thaw cycles and will move upward at a faster rate than those buried deeper · Degree of uplift related to age (uplift is cumulative; the longer an object is buried, the greater the upward displacement) · Tendency to force objects into vertical orientation · Disruption of stratigraphic boundaries (Johnson and Hansen 1974; Wood and Johnson 1978: 339-340; Holliday 2004: 279)		· Assessment of past/present local climate to identify potential for frost-related processes · Use of field descriptions to identify frost-related features · Micromorphological analysis to identify freeze-thaw structures, stratigraphic disruption, size-sorting (larger objects closer to surface) and vertical orientation of objects (Rapp and Hill 2006: 99-100; Karkanas and Goldberg 2019: 42)
Frost wedging · Fragmentation of artefacts and materials as a result of water expansion · Greater fragmentation in more porous materials · Greater fragmentation with more available water and environments/surface layers which undergo more freeze-thaw cycles (Goffer 2007: 417; Milek 2006: 85)		· Use of field descriptions to identify frost-related features · Micro-refuse analysis to assess fragmentation; fragments should be refitted where possible (van Vliet-Lanoë 1985: 129; Goldberg and Macphail 2006: 24-25; Milek 2006: 85)

Biological processes

Processes and Impacts	Examples	Research Strategies
Bioturbation		
Floralturbation · Vertical displacement of soil and artefacts during root growth · Permanent disruption of stratigraphic boundaries · Soils adhering to root-plates can be removed, displaced or inverted if uprooted (tree-throw) · Integrity of structures affected by plant activity (Wood and Johnson 1978: 328-333; Rapp and Hill 2006: 100-101)	· In Upper Tillygarmond, Aberdeenshire, bracken growth on a deserted settlement was found to severely impact clast-rich and clast-supported contexts. Field analysis indicated this was due to rhizomes exploiting inter-clast spaces and increasing the size of these voids. It was predicted that over time this would result in the destabilisation of clast-rich sediments and the fracturing of wall faces, slumping of rubble banks and general structure degradation. (Rees and Mills 1999: 13-15)	· Use of field descriptions to assess level of observable bioturbation (root channels, plants, trees) · Micromorphological analysis to detect root channels (Matthews et al. 1997: 291)
Faunalturbation · Vertical and/or horizontal displacement of soil and artefacts up to several metres via burrowing activity of mammals, invertebrates and molluscs · Permanent disruption of stratigraphic boundaries · Intensity of disruption varies according to species and/or population density · Burial of objects by surface accumulations (e.g. earthworm casts) · Presence of voids in soil microstructure	· Thin section analysis conducted on a wide range of cultivation contexts in the Bowmont Valley, south east Scotland, revealed that the burrowing, mixing, eating and excreting activities of soil animals resulted in the almost total loss of structural features characteristic of cultivation. (Davidson 2002)	· Use of field descriptions to assess level of observable bioturbation (animal burrows, excrement, presence of fauna in surrounding environment) · Micromorphological analysis to detect voids, faecal remains and calcium carbonate structures

· Destruction of archaeobotantical material (e.g. ingestion of carbonised seeds by earthworms) · Presence of coprolites, faecal spherulites (5-15μm), mollusc remains and calcium carbonate earthworm granules (0.1-2.5mm) · Production of 'pea-grit' layer after abandonment of earthworm aestivation chambers (Wood and Johnson 1978: 318-328; Stein 1983; Davidson et al. 1999; Canti 2003, 2007; Rapp and Hill 2006: 100-101; Tryon 2006; Durand et al. 2010; Kooistra and Pulleman 2010)		(Davidson et al. 1999; Grave and Kealhofer 1999; Durand et al. 2010: 170-174; Kooistra and Pulleman 2010)
Alteration of soil chemistry · Earthworm casts contain higher soluble concentrations of almost all soil elements · Intense earthworm activity may therefore result in higher pH, total and exchangeable Ca, exchangeable K and Mn, available P, and organic matter content (Stein 1983: 281)		· Micromorphological analysis to detect signs of earthworm activity (burrows, pellets) · Systematic rather than spot sampling to create generalised signature and avoid misinterpretation of localised values (Milek 2006: 84)
Animal activity		
Scavenging (including gifting of bones to household dogs) · Removal/horizontal displacement of bones by scavenging animals · Damage and fragmentation of bones · Greater damage to spongy and more frangible bones (e.g. infants, young juveniles) (Binford and Bertram 1977: 79; Meadow 1980: 68; Kent 1981)		· Examination of bones for indicators of animal activity (e.g. punctures, furrows)

Faecal deposition · Alteration to soil chemistry - increased organic matter content - elevated phosphates - elevated base levels - planar voids and dung spherulites - presence of authigenic minerals as a result of decay and diagenesis (Karkanas et al. 2000: 916; Shahack-Gross et al. 2004; Karkanas and Goldberg 2010: 529-530; Macphail and Goldberg 2018b: 602-607)		· Use of geochemical analysis, loss-on-ignition, pH and micromorphology to detect properties associated with manuring (organic matter content, phytoliths, coprolites, phosphates, acidity levels, faecal spherulites) · Use of faecal lipid biomarker analysis to detect and identify dung contributors (Karkanas and Goldberg 2010: 529-533; Macphail and Goldberg 2018: 602-607)
Trampling · Erosion of sites (risk and impact increases with heavy stocking) · Compaction of soil · Creation of horizontal orientations and planar voids · Damage to artefacts/structures		· Use of micromorphology to detect compaction, planar voids, horizontal distribution of minerals and microartefacts
Organic matter		
Decay of organic material · Loss of uncharred organic matter and artefacts · More rapid decay in warm, moist and oxidising conditions (least preserving conditions in soils that are seasonally wet but dry in summer) · Increased soil acidity due to the production of carbonic and humic acids following decomposition · Elevated levels of total organic carbon and other elements (P, N, Ca, Mg) · Uncharred materials can be preserved in anoxic waterlogged environments or very dry conditions (Kibblewhite et al. 2015: 250-251)		· Loss-on-ignition to assess organic matter content of sediments · Use of micromorphological analysis to identify organic staining, partially decomposed organic material and ecofacts indicative of organic matter presence (e.g. phytoliths) (Stolt and Lindbo 2010: 371-376)

Processes and Impacts	**Examples**	**Research Strategies**
Daily life and maintenance		
Trampling (including kicking/scuffing) · Vertical and horizontal size-sorting · Vertical displacement of artefacts - greater depth penetration of smaller artefacts - greater depth penetration in loose floor sediments · Horizontal displacement of artefacts and material - creation of 'marginal' and 'traffic' zone - migration of bulky items to margins of trampled area - random scatter of small- and medium-sized items in traffic area - very small items buried close to spot of deposition - greater displacement on more compact floor surfaces as less opportunity for burial - transportation of 'clods' of sediment on soles · Introduction and mixing of material from multiple locations/activities · Damage to artefacts (fragmentation, micro-chipping, abrasion) (Stockton 1973; Schiffer 1983: 679; Gifford-Gonzalez et al. 1985; Behrensmeyer et al. 1986; Olsen and Shipman 1988; Nielsen 1991; Banerjea et al. 2015: 97-98)	· At a Norse farmstead in Bornais, South Uist, elevated P, N and magnetic susceptibility values were recorded towards the east of the hearth and the entrance of the house. This was interpreted as reflecting ash that had been raked away from the heart and trampled or swept towards the entrance. *In situ* trampling activity was also identified through highly fragmented pottery sherds. (Marshall et al. 2005: 58-64; Bond and Lane 2005: 67; Sharples 2005: 81)	· Use of field descriptions and micromorphology to assess integrity of floor deposits · Micro-refuse and geochemical analysis to reconstruct floor components · Comparison of micro- and macro-refuse distribution patterns to identify horizontal displacement · Analysis of artefacts to assess damage (Goldberg 1983: 147-148; Matthews et al. 1997; Banerjea et al. 2015)

Deposition of floor cover material · E.g. ash, clay, sand, turf, mats, skins, plaster · Alteration of soil chemistry and/or organic matter content (effects dependent on type of cover used) · Introduction of micro-artefacts, insects and ecofacts · Mats can result in the 'sieving' of material, where the size of micro-aggregates are directly related to the mesh size of covering material · Removal of floor cover material limits accumulation of permanent floor sediments · Type, frequency and treatment of deposition material dependent on cultural habits, belief systems, perceptions of cleanliness etc. (Gé et al. 1993: 155-156; Boivin 2000; Milek 2012b; Macphail and Goldberg 2018a: 226-234)	· In a micromorphological study of pre-Norse structures at Bostadh Beach, Isle of Lewis, the material used for floor layers was found to depend on the location of that floor within the structure. At the entrance of Structure L, 21 individual floors were formed from alternating layers of well-humified peat and peaty turfs, whilst at the centre of the house, 17 individual floors had been derived from fire hearth material. (Tams 2003: 210)	· Micromorphological analysis to identify fine layers and components indicative of floor coverings (e.g. layers of articulated phytoliths, fine sediment stains, micro-artefacts, insects) · Use of lipid biomarker analysis to detect presence of lanolin if sheep skins used as covering (Matthews et al. 1997; Goffer 2007: 311-319; Milek 2012b: 132; Macphail and Goldberg 2018: 226-234)
Cleaning (discard, sweeping and hand removal) · General removal of objects and material from deposition area · Primary refuse deposition likely to be small artefacts (<2cm) · Formation of secondary refuse deposits (middens, use of ash as floor cover, use of organic material as fertiliser) · Increased damage of artefacts in secondary refuse deposits · Horizontal displacement of artefacts - hard-to-reach areas and marginal zones act as artefact traps - greater displacement during 'pick-up' cleaning - greater displacement of objects deemed hazardous, unsanitary or of little value - greater displacement where there is reduced	· Thin-section analysis on Iron Age structures at Old Scatness identified large amounts of raw peat fragments in the floor layers, suggesting it was either brought in for fuel or used as a floor spreading. They combined this with research into middens and soils surrounding the site and concluded that, when the floors of structures were cleaned out, the organic-rich material was placed in the fields rather than in the middens. (Guttmann et al. 2003: 5) · In Nairn, north east Scotland, researchers	· Use of field descriptions to identify areas of primary/secondary refuse deposition · Micro-refuse, geochemical and micromorphological analysis to acquire data on floor components · Analysis of spatial distribution patterns to track movement of material · Comparison of micro- and macro-refuse distribution patterns to identify horizontal displacement · Micromorphological analysis to identify potential cleaning patterns/episodes

living space - possible reuse of broken or chipped items in alternative tasks/locations · Effects of cleaning dependent on method, instruments used, frequency, floor surface, cultural habits, perceptions of cleanliness etc. (Murray 1980; Stevenson 1982; Hayden and Cannon, 1983; Arnold 1990: 918-919; Milek 2006: 79-80, 2012b: 133; Macphail and Goldberg 2018b)	identified post-medieval cleaning practices and tertiary deposition through soil depth survey. Substantial deepening of the topsoil (up to 120cm) and high fertility in the land surrounding the town was attributed to an urban composting process, whereby waste material, including peat ash, byre sands and old turf walls, accumulated in dunghills within the town before being deposited on the burgh lands. (Davidson et al. 2006)	(Matthews et al. 1997: 289; Milek 2006: 79-80; Banerjea et al. 2015)
Agriculture		
Keeping of animals · Alteration to soil chemistry and structure through dung deposition and fodder - increased organic matter content - elevated phosphates - elevated base levels - planar voids and dung spherulites from dung degradation · Increased earthworm activity and subsequent bioturbation as a result of elevated base levels · Trampling and depression of stabling area · Use and displacement of dung residues as manure, fuel, walling material, general discard (Bethell and Máté 1989: 9; Holliday & Gartner 2007; Friesem et al. 2014b: 77; Historic England 2015: 15)	· Multi-element analysis of recently abandoned farms in Shetland, Sutherland, Argyll and Perthshire identified high levels of phosphorus and zinc in known byre areas and attributed these to inputs of animal dung and bedding materials. In addition, midden areas were also found to contain elevated levels of phosphorus and zinc, indicating the discard of byre materials. (Wilson et al. 2005)	· Use of field descriptions to identify areas of possible animal tending · Use of geochemical analysis, loss-on-ignition and micromorphology to detect properties associated with manuring (organic matter content, phytoliths, phosphates, faecal spherulites) · Use of faecal lipid biomarker analysis to detect and identify dung contributors (Bull et al. 2001)

Field techniques (including clearance, manuring, irrigation) · Alteration to soil chemistry - manuring elevates phosphate levels - ash and additions to fertiliser enhance magnetic susceptibility - ash from clearance burning elevates level of K, Ca and Mg and charcoal and promotes translocation of clay and fine particles of charred plants · Increase in geogenic processes such as wind-borne soil erosion and colluviation · Increased organic matter content where manuring has been practiced · Increased earthworm activity and subsequent bioturbation (manuring elevates base levels) · Destruction, truncation and scarring of archaeology via ploughing · Reworking of soils and loss of stratigraphic positions (Macphail and Goldberg 1990; Davidson et al. 1998; Holliday 2004: 333; Goldberg and Macphail 2006: 193-210; Adderley et al. 2010)	· In a study on soil profiles from known cultivation contexts in south east Scotland (see above), researchers attributed extensive soil animal activity (bioturbation) to increased soil fertility as a result of manuring. (Davidson 2002) · During investigation into a prehistoric enclosure in Perthshire, plough furrows and field drains were found to have caused significant damage to the below-ground archaeological deposits and created a lattice effect on the subsoil surface. These scars were distinct from normal plough furrows in that they contained a mixture of topsoil and subsoil and penetrated some 0.18m into the subsoil, c 0.50m below the ground surface. (Burke 2002 in Oxford Archaeology 2002)	· Use of field description to identify landscape and soil features associated with agriculture · Loss-on-ignition to assess and compare organic matter content · Magnetic susceptibility to assess heat-affected inclusions · Micromorphological analysis to identify features associated with agriculture (e.g. dusty clay and silt coatings, bioturbation, phytoliths, charcoal) (Macphail et al. 1990; Macphail 1998; Holliday 2004: 332; Adderley et al. 2010)
Decay and abandonment		
Decay of construction materials · Formation of narrow, thin apron of wall material directly on the ground following decay of wall material during the effective life of a structure · Slope debris rapidly enlarged following abandonment and roof collapse · Slope of material angled away from wall · Fine-grained sediment caused by disintegration of		· Use of field descriptions to identify macroscopic remains, floor and roof deposits, and assess site integrity · Micromorphological analysis to assess stratigraphy and identify features associated with construction materials and decay

mudbrick, plaster or mortar · Discarded or decayed mortars commonly found as small fragments of calcareous cement surrounding sand grains (Macphail 1994; Friesem et al. 2014b: 73; Historic England 2015: 17-18; Karkanas and Goldberg 2019: 37-38)		
Roof collapse · Introduction of new material to floor deposits · Possible obscuration of direct contact between vegetal activity remains and vegetal roof remains (even microscopically) resulting in mixed floor-roof assemblages · Timing of collapse determines preservation of activity remains · Exposure of floor surfaces to weathering radically transforms deposits (e.g. accelerated organic decay, increased acidic conditions, promotion of bioturbation) (Milek 2012b: 124; Friesem et al. 2014b)	· In an investigation into the site formation processes affecting traditional Hebridean farmsteads, Smith (1996) was able to determine that the upper floor deposits were composed of straw thatch from roof collapse. These were distinct from the lower floor levels, which had been constructed from windblown sands and unvegetated deposits. (Smith 1996)	· Use of field descriptions to identify macroscopic remains, floor and roof deposits, and assess site integrity · Micromorphological analysis to assess stratigraphy and identify features associated with roof collapse
Removal of objects · General removal of objects and features if abandonment was planned · Storage of certain objects if residents expect to return · Removal influenced by potential for return, portability of objects, perceived value, proximity of new residence, mobility of residents, cultural habits and beliefs (Stevenson 1982; LaMotta and Schiffer 1999)		· Use of field descriptions to assess presence/condition/absence of features · Geochemical, micromorphological and micro-/macro-artefactual evidence to detect changes in deposition

Change of discard practices · Normal cleaning practices may cease if abandonment was planned, resulting in an accumulation of refuse - increased volume of artefacts and material - more clustered arrangements of refuse - creation of specialised refuse areas · Abandoned structures may be used as refuse dumps · Objects may be placed in meaningful ways and in significant locations (e.g. in postholes, hearths, thresholds) · Buildings and/or objects may be deliberately destroyed following abandonment (Stevenson 1982; Hayden and Cannon 1983; Deal 1985: 271-273; Schiffer 1985, 1989; Montgomery 1993; LaMotta and Schiffer 1999; Banerjea et al. 2015: 105)	· Structures in the Iron Age/Early Norse settlement at Old Scatness, Shetland, were used as rubbish dumps following their abandonment. Notably, this act of reuse and the rapid accumulation of material protected some of the floor layers from later disturbance. (Guttmann et al. 2003: 3) · At High Pasture Cave in Scotland, the remains of a woman and the associated disarticulated remains of a foetus and multiple neonates were placed on a staircase prior to the sealing of the cave entrance in the early centuries AD (Birch 2005, 2006; Tucker 2010: 83, 205)	· Use of field descriptions to assess collapse patterns, artefact distribution, evidence of destruction etc. · Micromorphological analysis to assess microstratigraphy and identify changes in type and nature of sediment deposition (Milek 2012b: 133; Banerjea et al. 2015: 103-105)

Appendix 2

Research Paper Supplementary Materials

The following appendix contains the Supplementary Materials that were provided with each of the research papers, excluding Chapter 5 for which no Supplementary Material was required.

Where the Supplementary Materials were provided in Word document format (.docx), their format has been retained and provided like-for-like here. Where materials were supplied as Excel files (.xls), their information has been converted to a more convenient Word table format for accessibility purposes.

The contents of this appendix are as follows:

Chapter 4

S1: List of search terms used in analysis of excavation literature

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List of search terms used in analysis of excavation literature

- Hyphens not included in search terms (except on occasional variations of spelling – e.g. thin-section)
- Hyphens used to denote where word could have multiple endings (e.g. searching for 'sampl' could produce results for sampling, sample, samples, sampled etc.)

<u>Analysis:</u>

- Soil / sediment
- Sampl-
- Organic / loss-
- Phosph-
- Floor / occupation
- Micromorph- / thin(-)section
- Magnetic
- Grid
- Bulk / chemical

<u>Site formation processes:</u>

- Erosion / erod-
- Wind / (a)eolian / blow / sand
- Water / fluvi- / flood / alluvi- / wave
- Slop- / colluvi- / hill(-)wash / slump / tumble / creep
- pH / acid- / alkali-
- Formation / process
- Leach- / translocat- / pan / iron(-) / downward / percolat-
- Turbation / worm / burrow / root / tree
- Cut / truncat- / disturb-
- Preserv- / bone
- Intrusi-
- Scaveng- / gnaw / animal / faec- / dung
- Clean- / sweep- / trampl- / discard
- Cropmark / agriculture / cultivat- / burn- / plough
- Collapse / decay / abandon- / robb- / reuse / damag- / degrad-
- Fragment-
- Frost / freez-

Chapter 6

SM1: Micromorphology locations, descriptions and interpretations

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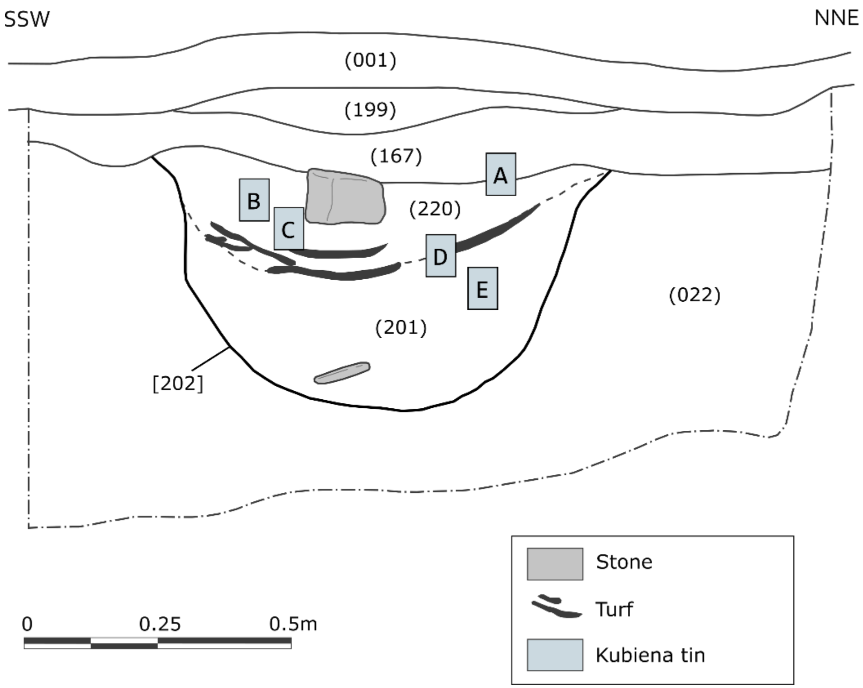
Supplementary Material 1; Figure 1 Section drawing and photograph - thin-section locations; GS16-A, GS16-B, GS16-C, GS16-D, GS16-E



Notes:

- Composite sketch from 2015 and 2016 section drawings (based on Strachan et al. 2019: 46)
- Layers (001) and (199) removed during the 2015 excavation season

Supplementary Material 1; Table 1.1 GS16-A: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary**	Structure					Void Type*				Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels and Vughs	Planar (Random)	Planar (Horizontal)	Compound Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
167	57 mm	Clear	Organic silt loam	Spongy with channels and crumb	Porphyric; unevenly distributed close to open porphyric	20:80	45	▪▪▪▪▪▪▪▪			▪▪▪▪▪▪▪	Dark brown; dotted	Dark brown	Stipple-speckled; localised undifferentiated
220.1	22 mm	Bottom of slide	Sandy silt loam	Spongy and crumb with localised channels	Porphyric; unevenly distributed close to open porphyric	30:70	35	▪▪▪▪▪▪▪▪▪			▪▪▪▪▪▪	Mid-brown; dotted	Yellowish-brown	Stipple-speckled

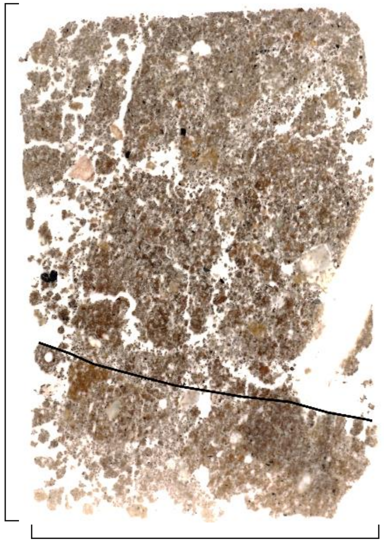
Context and Microstratigraphic Unit	Organic Matter						Inclusions			Pedofeatures		
	Charred			*Uncharred*								
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Bone	Intrusive Aggregates	Rubified Fine Mineral Material	Fe/Mn	Fe Intercalations	Excremental
167	+		+	▪▪	▪	▪▪▪▪		▪▪				▪▪▪▪
220.1	+		▪	▪▪	▪	▪▪▪		▪▪				▪▪▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)

* frequency class for voids refers to % total void space (following Bullock et al. 1985)

** lower boundary described using the following definitions - **knife edge** (razor sharp), **sharp** (very clear and abrupt change), **clear** (transition occurs over less than 1cm), **diffuse** (transition is greater than 1cm) and **bottom of slide** (lower boundary of layer extends beyond base of thin-section); modifiers such as **incline** also used to define their character

Supplementary Material 1; Table 1.2 GS16-A: Thin-section interpretation



7.4cm

5.1cm

Context	Summary of key features	Interpretation
167	Organic sandy silt loam with a mixed fabric containing occasional intrusive aggregates of a lighter-coloured, less-organic material with a higher clay component. Uncharred plant component consists of slightly to moderately decomposed roots. No anthropogenic inclusions other than trace charcoal.	Heavily bioturbated surface overlying a filled pit within annexe. Deposited during sealing of the pit and/or maintenance of the annexe floor. NB. The pit was opened in 2015 and re-excavated for sampling.
220.1	Sandy silt loam containing occasional intrusive aggregates of a lighter-coloured, less-organic material. No anthropogenic inclusions other than trace charcoal. Quantification achieved using 220.1 in GS16-A, GS16-B and GS16-C.	Bioturbated fill of the annexe pit. Deposited as the secondary fill of the pit or during the sealing of the primary fill (201). May represent an A or amended A horizon that has lost some granular structure (possibly from a turf).

Supplementary Material 1; Table 2.1 GS16-B: Thin-section description

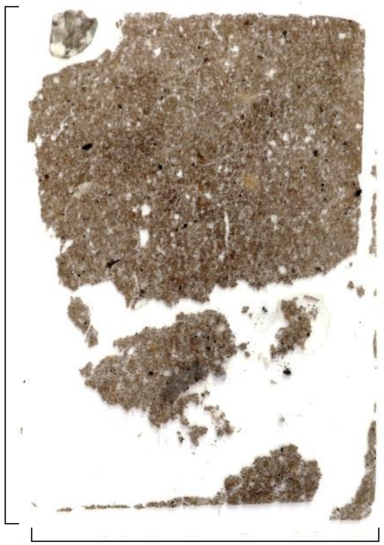
			Structure					Void Type*				Fine Material		
Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels and Vughs	Planar (Random)	Planar (Horizontal)	Compound Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
220.1	74 mm	Bottom of slide	Sandy silt loam	Spongy and crumb with localised channels	Porphyric; unevenly distributed close to open porphyric	30:70	35	▪▪▪▪▪▪▪▪▪			▪▪▪▪▪▪	Mid-brown; dotted	Yellowish-brown	Stipple-speckled

Context and Microstratigraphic Unit	Organic Matter						Inclusions			Pedofeatures		
	Charred			*Uncharred*								
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Bone	Intrusive Aggregates	Rubified Fine Mineral Material	Fe/Mn	Fe Intercalations	Excremental
220.1	+		▪	▪▪	▪	▪▪▪		▪▪				▪▪▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

Supplementary Material 1; Table 2.2 GS16-B: Thin-section interpretation

7.4cm



5.0cm

Context	Summary of key features	Interpretation
220.1	Sandy silt loam containing occasional intrusive aggregates of a lighter-coloured, less-organic material. Uncharred plant component consists of slightly to moderately decomposed roots. No anthropogenic inclusions other than trace charcoal. Quantification achieved using 220.1 in GS16-A, GS16-B and GS16-C. Majority of the lower half of the slide lost as a result of difficult sampling conditions. Area excluded from quantification and analysis.	Bioturbated fill of the annexe pit. Deposited as the secondary fill of the pit or during the sealing of the primary fill (201). May represent an A or amended A horizon that has lost some granular structure (possibly from a turf).

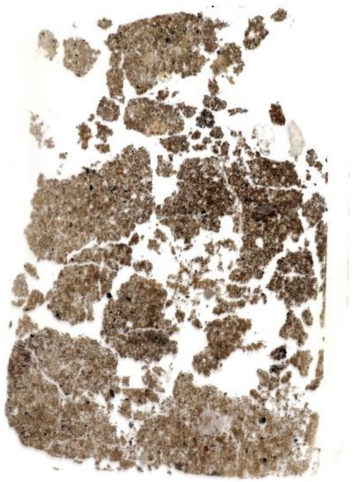
Supplementary Material 1; Table 3.1 GS16-C: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Structure					Void Type*				Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels and Vughs	Planar (Random)	Planar (Horizontal)	Compound Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
220.1	73 mm	Bottom of slide	Sandy silt loam	Spongy and crumb with localised channels	Porphyric; unevenly distributed close to open porphyric	30:70	35	▪▪▪▪▪▪▪▪▪			▪▪▪▪▪▪	Mid-brown; dotted	Yellowish-brown	Stipple-speckled

Context and Microstratigraphic Unit	Organic Matter						Inclusions			Pedofeatures		
	Charred			*Uncharred*								
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Bone	Intrusive Aggregates	Rubified Fine Mineral Material	Fe/Mn	Fe Intercalations	Excremental
220.1	+		▪	▪▪	▪	▪▪▪		▪▪				▪▪▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

Supplementary Material 1; Table 3.2 GS16-C: Thin-section interpretation



7.3cm

5.0cm

Context	Summary of key features	Interpretation
220.1	Sandy silt loam containing occasional intrusive aggregates of a lighter-coloured, less-organic material. Uncharred plant component consists of slightly to moderately decomposed roots. No anthropogenic inclusions other than trace charcoal. Quantification achieved using 220.1 in GS16-A, GS16-B and GS16-C. Substantial area of the slide lost as a result of difficult sampling conditions, including majority of the upper half. Quantification and analysis were achieved using areas of better-preserved fabric.	Bioturbated fill of the annexe pit. Deposited as the secondary fill of the pit or during the sealing of the primary fill (201). May represent an A or amended A horizon that has lost some granular structure (possibly from a turf).

Supplementary Material 1; Table 4.1 GS16-D: Thin-section description

			Structure					Void Type*				Fine Material		
Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels and Vughs	Planar (Random)	Planar (Horizontal)	Compound Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
220.2	21 mm	Sharp; incline	Organic sandy silt loam	Granular and spongy	Porphyric; unevenly distributed close to open porphyric	25:75	45	▪▪▪▪▪▪▪▪			▪▪▪▪▪▪▪	Dark brown; mid-brown; dotted	Dark brown; yellowish-brown	Stipple-speckled; localised undifferentiated
201	65 mm	Bottom of slide	Silt loam	Spongy with localised channels	Porphyric; unevenly distributed close to open porphyric	15:85	30	▪▪▪▪▪▪▪▪▪▪			▪▪▪▪	Yellowish-brown; dotted	Yellow	Mosaic-speckled

Context and Microstratigraphic Unit	Organic Matter						Inclusions			Pedofeatures		
	Charred			*Uncharred*								
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Bone	Intrusive Aggregates	Rubified Fine Mineral Material	Fe/Mn	Fe Intercalations	Excremental
220.2	▪▪▪	+	▪▪▪	▪	+	▪▪▪▪		▪				▪▪▪▪▪
201	▪▪	▪	▪	+	+	▪▪		▪▪				▪▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

Supplementary Material 1; Table 4.2

GS16-D: Thin-section interpretation

7.5cm

5.0cm

Context	Summary of key features	Interpretation
220.2	Organic sandy silt loam containing elevated wood charcoal and charred amorphous organic matter. Identifiable charred component includes monocot stems and pine (max. 4 mm x 2 mm). Excremental pedofeatures are mammilate and granular excrement.	Heavily bioturbated fill of the annexe pit, likely representing the truncated/decomposed Oa horizon of an inverted turf. Deposited during sealing of the primary fill.
201	Silt loam with limited organic matter and intrusive aggregates of compacted greyish-yellow clay (2-5% porosity) with unistriated b-fabric. Aggregates have lenses of horizontally-orientated minerals but do not contain any horizontal voids. Main fabric has abundant, poorly-sorted laith-shaped minerals, ranging in length from c. 40µm to 2 mm. Voids are primarily earthworm channels (majority empty but some partially-infilled with organic material from the layers above - intrusive material excluded from quantification). No anthropogenic inclusions other than the charred wood (max. 6 mm x 3 mm), which includes pine and diffuse porous charcoal (likely birch/willow family).	Bioturbated fill of the annexe pit. Deposited as the primary fill. Origin of fill is unclear but does not appear to represent domestic waste.

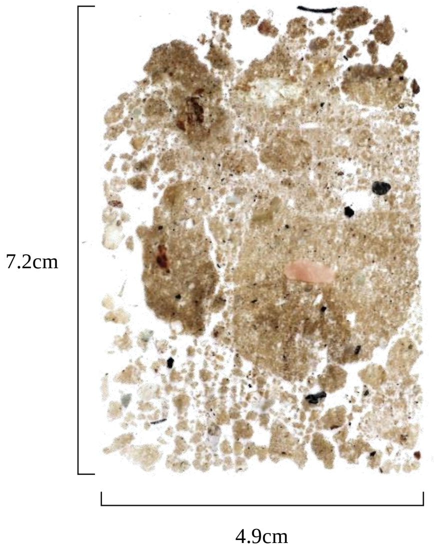
Supplementary Material 1; Table 5.1 GS16-E: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Structure					Void Type*				Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels and Vughs	Planar (Random)	Planar (Horizontal)	Compound Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
201	72 mm	Bottom of slide	Silt loam	Spongy with localised channels	Porphyric; unevenly distributed close to open porphyric	15:85	30	▪▪▪▪▪▪▪▪▪▪			▪▪▪▪	Yellowish-brown; dotted	Yellow	Mosaic-speckled

Context and Microstratigraphic Unit	Organic Matter						Inclusions			Pedofeatures		
	Charred			*Uncharred*								
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Bone	Intrusive Aggregates	Rubified Fine Mineral Material	Fe/Mn	Fe Intercalations	Excremental
201	▪▪	▪	▪	+	+	▪▪		▪▪				▪▪▪

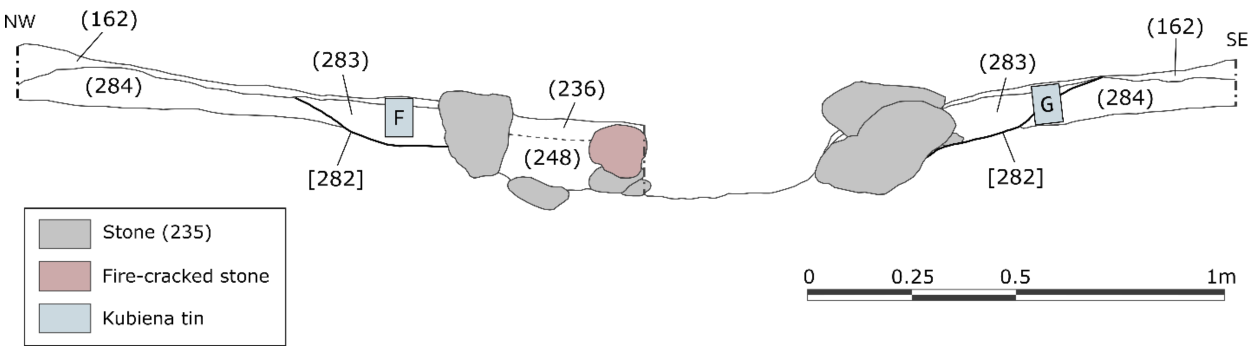
+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

Supplementary Material 1; Table 5.2 GS16-E: Thin-section interpretation



Context	Summary of key features	Interpretation
201	Silt loam with limited organic matter and intrusive aggregates of compacted greyish-yellow clay (2-5% porosity) with unistriated b-fabric. Aggregates have lenses of horizontally-orientated minerals but do not contain any horizontal voids. Main fabric has abundant, poorly-sorted lath-shaped minerals, ranging in length from c. 40µm to 2 mm. Voids are primarily earthworm channels (majority empty but some partially-infilled with organic material from the layers above - intrusive material excluded from quantification). No anthropogenic inclusions other than the charred wood, which includes pine and diffuse porous charcoal (likely birch/willow family). Lower area of the slide damaged as a result of difficult sampling conditions. Quantification and analysis were achieved using areas of better-preserved fabric in GS16-D and GS16-E.	Bioturbated fill of the annexe pit. Deposited as the primary fill. Origin of fill is unclear but does not appear to represent domestic waste.

Supplementary Material 1; Figure 2 Section drawing and photographs - thin-section locations; GS16-F, GS16-G



Notes:

- The position of the layers identified in thin-section do not correspond directly to those recorded during excavation (e.g. GS16-G did not sufficiently capture (162) or the cut [282])
- Probable that profile of cut [282] changed deeper into the section where the sample was recovered

Supplementary Material 1; Table 6.1 GS16-F: Thin-section description

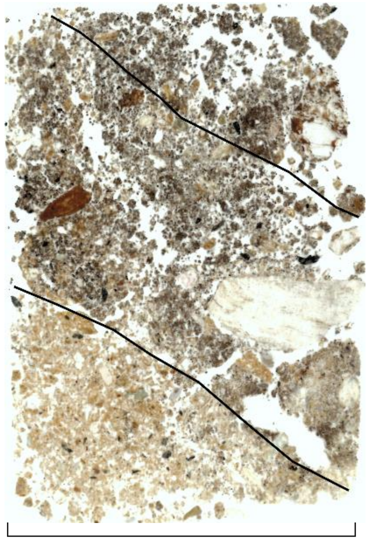
Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Structure					Void Type*				Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels and Vughs	Planar (Random)	Planar (Horizontal)	Compound Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
162	19 mm	Diffuse; incline	Organic sandy silt loam	Moderately to well-developed granular with channels and localised subangular blocky	Porphyric; unevenly distributed close to open porphyric	55:45	40	▪▪▪▪▪▪▪▪	+	▪▪	▪▪▪▪▪▪	Dark brown; dotted	Dark brown	Stipple-speckled; localised undifferentiated
283a	36 mm	Sharp; incline	Sandy silt loam	Moderately to well-developed granular with channels and localised spongy	Porphyric; unevenly distributed close to open porphyric	60:40	50	▪▪▪▪▪▪▪	+		▪▪▪▪▪▪▪▪	Dark brown; yellowish-brown; dotted	Dark brown; brownish-yellow	Stipple-speckled
284	32 mm	Bottom of slide	Sandy loam	Spongy with channels and localised crumb structure	Porphyric; unevenly distributed close to open porphyric	50:50	35	▪▪▪▪▪▪▪▪▪▪			▪▪▪▪	Yellowish-brown; speckled	Yellow	Stipple-speckled

Context and Microstratigraphic Unit	Organic Matter						Inclusions			Pedofeatures		
	Charred			*Uncharred*								
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Bone	Intrusive Aggregates	Rubified Fine Mineral Material	Fe/Mn	Fe Intercalations	Excremental
162	▪	+	▪	▪	▪	▪▪▪▪		▪▪▪	+	+		▪▪▪▪▪
283a	▪	+	▪▪	+	▪	▪▪▪		▪▪▪▪		▪		▪▪▪▪
284	+		▪	+	▪	+				+		▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

Supplementary Material 1; Table 6.2 GS16-F: Thin-section interpretation

7.5cm



5.1cm

Context	Summary of key features	Interpretation
162	Organic sandy silt loam with a mixed fabric containing intrusive aggregates (likely context 284 or natural subsoil). No anthropogenic inclusions other than limited charcoal (max. 3 mm x 1 mm). Areas of better-preserved fabric and three distinct aggregates in the upper right corner (accounting for approximately 10% of the layer) with lower porosity, horizontal planar voids and horizontal orientation of charcoal and minerals.	Heavily bioturbated occupation surface within living area of the house. Occasional fragments of surviving relic floor. Lack of anthropogenic inclusions may have resulted from maintenance practices and/or use of floor coverings, in addition to post-depositional processes.
283a	Sandy silt loam with a mixed fabric containing intrusive aggregates of lighter-coloured material (likely context 284) and subangular pebbles (max. 23 mm x 10 mm). No anthropogenic inclusions other than limited charcoal. Fe/Mn pedofeatures are primarily pseudomorphs of plant residues and amorphous organic material, with very occasional Fe nodules. Around 10% of the layer was disturbed by a partially-infilled earthworm channel (43 mm x 5 mm), with the area excluded from quantification.	Heavily bioturbated fill of cut for stone hearth, deposited during construction of the hearth. Appears to be a mixture of A and B horizons.
284	Sandy loam with a relatively compacted structure containing trace amorphous organic matter and limited charred inclusions. Channels contain excremental worm material and organic fabric from upper layers.	Redistributed subsoil deposited during construction of the hearth.

Supplementary Material 1; Table 7.1 GS16-G: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Structure					Void Type*				Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels and Vughs	Planar (Random)	Planar (Horizontal)	Compound Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
283b	73 mm	Bottom of slide / Diffuse; incline	Sandy silt loam	Moderately to well-developed granular; spongy and channels	Porphyric; unevenly distributed close to open porphyric	55:45	45	▪▪▪▪▪▪▪▪▪	+		▪▪▪▪▪▪	Brown; yellowish-brown; dotted	Brown; brownish-yellow	Stippled-speckled
284**	26 mm	Bottom of slide	Sandy loam	Crumb/granular with spongy and channels	Porphyric; unevenly distributed close to open porphyric	50:50	35	▪▪▪▪▪▪▪▪▪▪	+	+	▪▪▪▪▪	Yellowish-brown; brown; dotted	Brownish-yellow	Stippled-speckled

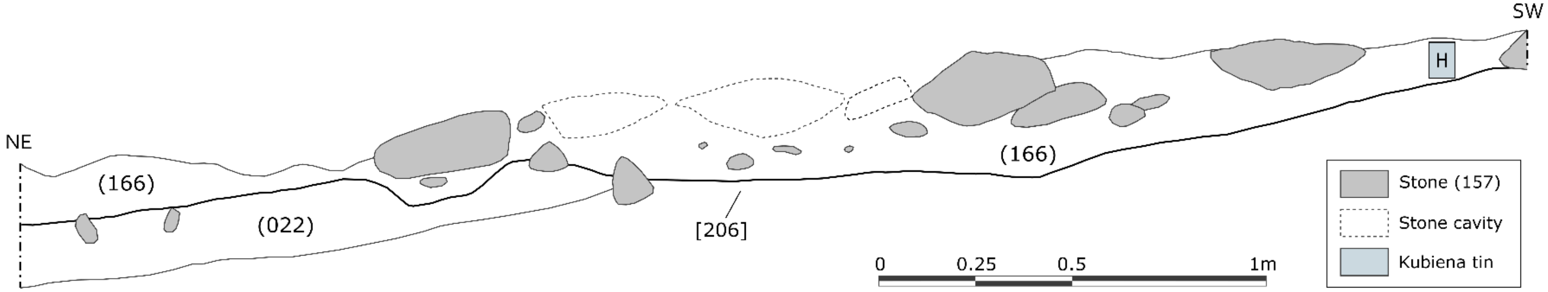
Context and Microstratigraphic Unit	Organic Matter						Inclusions			Pedofeatures		
	Charred			*Uncharred*								
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Bone	Intrusive Aggregates	Rubified Fine Mineral Material	Fe/Mn	Fe Intercalations	Excremental
283b	▪	+	▪	+	+	▪▪▪		▪▪▪		▪		▪▪▪
284**	▪	+	▪	+	+	▪▪		n/a (see **)		+		▪▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)
** labelled as context 284 during excavation but more likely to be a commingled deposit; see note in Table 7.2

Supplementary Material 1; Table 7.2 GS16-G: Thin-section interpretation

Context	Summary of key features	Interpretation
283b	Sandy silt loam with a mixed fabric containing intrusive aggregates of lighter-coloured material (likely context 284) and subangular pebbles (max. 25 mm x 7 mm). More compacted and decreasing granular microstructure from middle of layer towards base of slide. Concentration of amorphous organic matter is less extensive than context 283 in GS16-F. Approximately 15% of this layer is composed of a large vermiform (54 mm x 11 mm) that runs subparallel to the central axis; the area and material was excluded from quantification.	Bioturbated fill of cut for stone hearth, deposited during construction of the hearth. Appears to be a mixture of A and B horizons.
284**	Sandy loam with a more compacted structure and lighter colour than context 283. Colour is still significantly darker than context 284 in GS16-F and has a more pronounced crumb structure, with a significant number of empty and partially-filled earthworm channels. Possible that bioturbation is more pronounced in this layer. ** This area of the slide is most likely a mixed deposit of contexts 283 and 284, with no discernible boundary captured in thin-section.	Redistributed subsoil deposited during construction of the hearth. ** Likely to be commingled 283 and 284 fabric that has become mixed via bioturbation and/or during construction of the hearth.

Supplementary Material 1; Figure 3 Section drawing and photographs - thin-section location; GS16-H



Supplementary Material 1; Table 8.1 GS16-H: Thin-section description

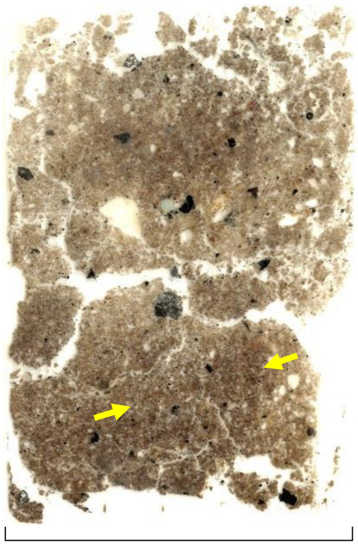
Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Structure					Void Type*				Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels and Vughs	Planar (Random)	Planar (Horizontal)	Compound Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
166	74 mm	Bottom of slide	Organic sandy silt loam	Spongy with crumb and localised subangular blocky	Porphyric; unevenly distributed close to open porphyric	20:80	30	▪▪▪▪▪▪▪▪▪▪	▪▪	▪	▪▪▪▪	Brown; dark brown; dotted	Yellowish-brown; brown	Stipple-speckled

Context and Microstratigraphic Unit	Organic Matter						Inclusions			Pedofeatures		
	Charred			*Uncharred*								
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Bone	Intrusive Aggregates	Rubified Fine Mineral Material	Fe/Mn	Fe Intercalations	Excremental
166	▪	▪▪	▪▪	▪	▪	▪▪▪▪	▪	▪	+	+		▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

Supplementary Material 1; Table 8.2 GS16-H: Thin-section interpretation

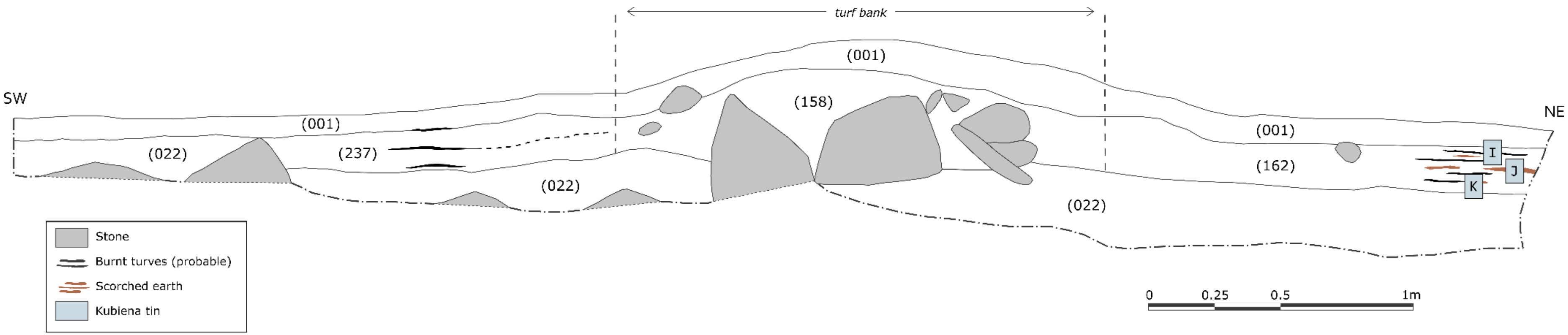
7.4cm



5.1cm

Context	Summary of key features	Interpretation
166	Organic sandy silt loam with a mixed fabric containing a notable charred plant component. Includes decomposed and partially-decomposed plant matter that has been burnt (max. 5 mm), cereal grains, monocot stems and small seeds (c. 200µm). Charred young wood component (max. 3 mm) includes pine and diffuse porous charcoal (likely birch/willow family), and a single fragment of 2 y/o roundwood hazel. Inclusion of a single fractured bone fragment with Fe bonding to the Ca and P of the bone. Organic matter and compaction increases towards the bottom of the thin-section, with localised subangular blocky microstructure identified in the most compacted areas. At least five sublinear areas of darker, less porous spongy microstructure identified across the layer (max. 37 mm x 2 mm; example indicated between arrows), each containing a small number of horizontal and sub-horizontal planar voids.	Matrix of stone flooring within byre-end of the structure. Deposited during purposeful infilling of byre cut. Horizontal cracks and compacted zones indicate trampling within this area of the structure. Charred component may be the residues of hearth waste or organic material associated with byre activities (e.g. animal feed, bedding, wattle partitions).

Supplementary Material 1; Figure 4 Section drawing and photographs - thin-section locations; GS16-I, GS16-J, GS16-K



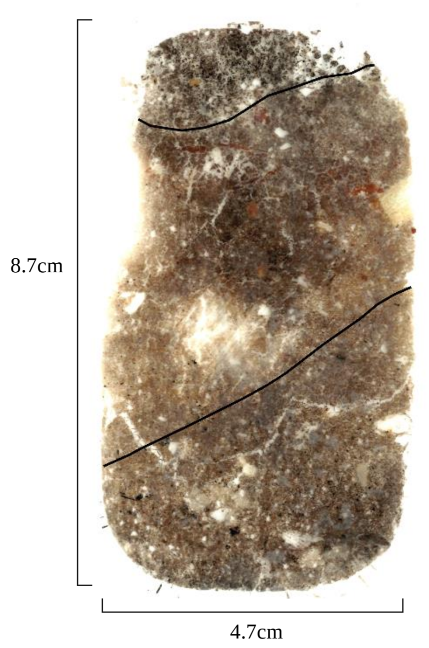
Supplementary Material 1; Table 9.1 GS16-I: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Structure: Textural Class	Structure: Microstructure	Structure: Course/Fine (100µm) Related Distribution	Structure: Course:Fine (100µm) Ratio	Structure: Porosity (%)	Void Type*: Channels and Vughs	Void Type*: Planar (Random)	Void Type*: Planar (Horizontal)	Void Type*: Compound Packing Voids	Fine Material: Nature of Fine Material (PPL)	Fine Material: Colour of Fine Material (OIL)	Fine Material: Birefringence Fabric (XPL)
001	16 mm	Sharp	Very organic sandy silt loam	Granular	Porphyric; unevenly distributed close to open porphyric	25:75	45	▪▪▪▪▪			▪▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Dark brown; black	Undifferentiated
162.1	44 mm	Clear; incline	Very organic sandy silt loam	Granular	Porphyric; unevenly distributed close to open porphyric	25:75	25	▪▪▪▪▪▪			▪▪▪▪▪▪▪▪▪	Dark brown; orangish-brown; dotted	Dark brown; orangish-brown	Stipple-speckled; localised undifferentiated
162.2	39 mm	Bottom of slide	Organic sandy silt loam	Spongy with localised crumb structure and channels	Porphyric; unevenly distributed close to open porphyric	30:70	25	▪▪▪▪▪▪▪▪▪▪			▪▪▪▪▪	Mid-brown; dotted	Yellowish-brown	Stipple-speckled

Context and Microstratigraphic Unit	Organic Matter: Charred: Wood (Charcoal)	Organic Matter: Charred: Plant	Organic Matter: Charred: Amorphous Organic Matter	Organic Matter: Uncharred: Plant	Organic Matter: Uncharred: Fungal Sclerotia	Organic Matter: Uncharred: Amorphous Organic Matter	Inclusions: Bone	Inclusions: Intrusive Aggregates	Inclusions: Rubified Fine Mineral Material	Pedofeatures: Fe/Mn	Pedofeatures: Fe Intercalations	Pedofeatures: Excremental
001	+		+	▪▪▪	▪	▪▪▪▪▪▪▪				▪		▪▪▪▪▪▪▪
162.1	+		+	▪▪	▪	▪▪▪▪▪		▪▪	▪	▪▪	▪▪	▪▪▪▪▪▪
162.2	▪▪	▪	▪▪▪	▪	+	▪▪▪▪		▪▪▪	▪▪	+		▪▪▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%) (following Bullock et al. 1985)
* frequency class for voids refers to % of total void space (following Stoops 2021: 73, section 5.2.4.)

Supplementary Material 1; Table 9.2 GS16-I: Thin-section interpretation



Context	Summary of key features	Interpretation
001	Very organic sandy silt loam with a well-developed granular microstructure and significant uncharred plant component (primarily fresh and slightly decomposed roots). No anthropogenic inclusions other than trace charcoal.	Modern turf/heather topsoil.
162.1	Very organic sandy silt loam with a moderately to well-developed granular microstructure; individual aggregates are smaller than those in 001. Presence of intrusive soil aggregates with a lighter colour (yellowish-brown; dotted) and spongy microstructure (likely the natural subsoil, context 022). Excremental pedofeatures are mammilate and granular excrement. Uncharred plant component consists of slightly to moderately decomposed roots; no anthropogenic inclusions other than trace charcoal. Fe/Mn nodules are primarily Fe preferentially bonding with plant and amorphous organic matter; Fe intercalations are restricted to the upper third of the layer. Around 10% of what was captured in thin-section had been thinned during the manufacturing process (area excluded from quantification).	Heavily bioturbated soil with evidence of digging. Appears to represent an ancient A or AB horizon, possibly from a turf whose O horizon has been truncated. Deposited during construction of turf stack (e.g. wall or internal feature). Presence of Fe/Mn nodules and Fe intercalations (not recognized elsewhere on the site) may indicate that the turf was sourced from a periodically waterlogged environment.
162.2	Organic sandy silt loam with predominately spongy microstructure, organic acid pigmentation, intrusive soil aggregates and occasional Fe nodules. Likely to be the same layer as 162.2 captured in GS16-J (see below); quantification has been achieved using both slides.	Bioturbated soil with evidence of digging. May be an A (or amended A) horizon that has lost its granular structure. Could also represent the A horizon of a non-inverted turf with a truncated O horizon. Deposited during construction of turf stack (e.g. wall or internal feature).

Supplementary Material 1; Table 10.1 GS16-J: Thin-section description

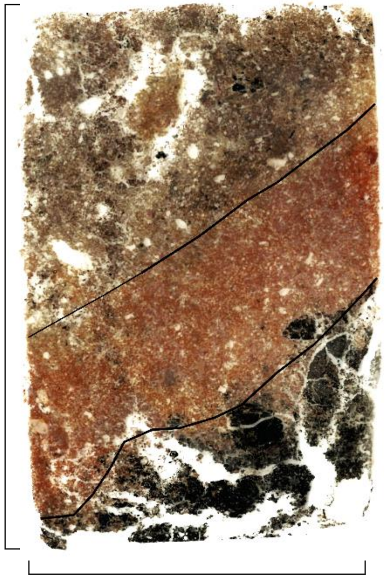
Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Structure					Void Type*				Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels and Vughs	Planar (Random)	Planar (Horizontal)	Compound Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
162.2	43 mm	Sharp; incline	Organic sandy silt loam	Spongy with localised crumb structure and channels	Porphyric; unevenly distributed close to open porphyric	30:70	25	▪▪▪▪▪▪▪▪▪▪			▪▪▪▪▪	Mid-brown; dotted	Yellowish-brown	Stipple-speckled
162.3	29 mm	Sharp; incline	Sandy silt loam	Spongy with localised crumb structure and channels	Porphyric; unevenly distributed close to open porphyric	20:80	20	▪▪▪▪▪▪▪▪▪▪			▪▪▪▪	Orange; orangish-brown; speckled	Orange; yellowish-brown	Stipple-speckled
162.4	30 mm	Bottom of slide	Organic matter	Spongy and granular with channels	Porphyric; unevenly distributed close to open porphyric	60:40	50	▪▪▪▪▪▪▪▪▪▪			▪▪▪▪	Black; orangish-brown; dotted	Black; orange to yellowish-brown	Undifferentiated; localised stipple-speckled

Context and Microstratigraphic Unit	Organic Matter						Inclusions			Pedofeatures		
	Charred			*Uncharred*								
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Bone	Intrusive Aggregates	Rubified Fine Mineral Material	Fe/Mn	Fe Intercalations	Excremental
162.2	▪▪	▪	▪▪▪	▪	+	▪▪▪▪		▪▪▪	▪▪	+		▪▪▪▪
162.3			▪	+	+	▪▪			▪▪▪▪▪▪▪▪	▪		▪▪
162.4	▪▪▪▪▪	+	▪▪▪▪▪	▪	+	▪		▪▪	▪▪	+		▪▪▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%) (following Bullock et al. 1985)
* frequency class for voids refers to % of total void space (following Stoops 2021: 73, section 5.2.4.)

Supplementary Material 1; Table 10.2 GS16-J: Thin-section interpretation

7.5cm



5.0cm

Context	Summary of key features	Interpretation
162.2	Organic sandy silt loam with predominately spongy microstructure, organic acid pigmentation, intrusive soil aggregates and occasional Fe nodules. Likely to be the same layer as 162.2 captured in GS16-I (see above); quantification has been achieved using both slides. More evidence of bioturbation in 162.2 in GS16-J than in GS16-I, with around 10% of what was captured being disturbed by a large earthworm channel (39 mm x 6 mm), partially-infilled with smaller soil aggregates (intrusive material avoided during quantification). Content 162.2 in GS16-J also contains a higher quantity of charred wood and amorphous organic matter than in GS16-I, which increases down 162.2 and across both slides. The transition appears too gradual to be considered separate layers. Presence of large intrusive soil aggregates (yellowish-brown; dotted - max. 20 mm x 6 mm) with a similar fabric to the site's natural subsoil (022).	Bioturbated soil with evidence of digging. May be an A (or amended A) horizon that has lost its granular structure. Could also represent the A horizon of a non-inverted turf with a truncated O horizon. Deposited during construction of turf stack (e.g. wall or internal feature).
162.3	Bright orange, compact sandy silt loam with almost all fine material rubified by heating. Contains limited amorphous organic matter and no anthropogenic inclusions other than very limited charred amorphous material.	Heat-affected, organic-deficient soil with evidence of digging. Likely represents a burnt Bfe or AB horizon in a non-inverted turf. Deposited during construction of turf stack (e.g. wall or internal feature).
162.4	Extremely organic layer, primarily composed of charred and partially-charred amorphous organic matter and wood. Charred amorphous component largely consists of partially decomposed plant matter that contains occasional sand particles The charred wood component (max. 11 mm x 5 mm) appears to be largely deciduous; identifiable fragments are diffuse porous, most likely from the birch/willow family. Uncharred plant matter consists of slightly to moderately decomposed roots in channels. Fine material is very limited but displays rubification. Channels have also introduced rubified material from the layer above (162.4).	Bioturbated organic layer with almost no soil component. Partially decomposed organic matter with sand may be evidence of peat but overall profile is more indicative of turf. Likely represents a burnt O horizon in an additional non-inverted turf. Deposited during construction of turf stack (e.g. wall or internal feature). The significant wood component suggests an additional source of material, possibly the remains of wooden artefacts or an associated structure, such as a wattle-panel.

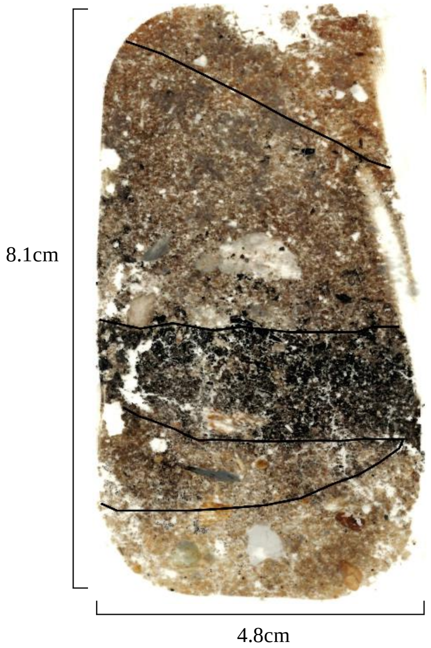
Supplementary Material 1; Table 11.1 GS16-K: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Structure					Void Type*				Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels and Vughs	Planar (Random)	Planar (Horizontal)	Compound Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
162.5	18 mm	Sharp; incline	Sandy silt loam	Spongy with localised crumb structure and channels	Porphyric; unevenly distributed close to open porphyric	20:80	20	■■■■■■■■■■			■■■■■	Orange; orangish-brown; speckled	Orange; yellowish-brown	Stipple-speckled
162.6	33 mm	Sharp	Sandy silt loam	Spongy with localised crumb structure	Porphyric; unevenly distributed close to open porphyric	30:70	30	■■■■■■■■■■			■■■	Mid-brown; dotted	Yellowish-brown	Mosaic-speckled
162.7	12 mm	Sharp	Organic matter	Spongy with granular and localised channels	Porphyric; unevenly distributed close to open porphyric	20:80	35	■■■■■■■■■■			■■■■	Black; dark brown; dotted	Black; orangish-yellow	Undifferentiated; localised mosaic-speckled
162.8	10 mm	Clear	Sandy silt loam	Crumb and spongy with localised channels	Porphyric; unevenly distributed close to open porphyric	35:65	40	■■■■■■■■■■			■■■■■	Yellowish-brown; dark brown; dotted	Orangish-yellow; yellowish-brown	Stipple-speckled
022	16 mm	Bottom of slide	Sandy loam	Spongy with localised channels	Porphyric; unevenly distributed close to open porphyric	55:45	25	■■■■■■■■■■			■■	Yellowish-brown; dotted	Orangish-yellow	Stipple-speckled

Context and Microstratigraphic Unit	Organic Matter						Inclusions			Pedofeatures		
	Charred			*Uncharred*								
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Bone	Intrusive Aggregates	Rubified Fine Mineral Material	Fe/Mn	Fe Intercalations	Excremental
162.5		+	■		+	■		■■	■■■■■■	+	■	■■■■
162.6	■■		■■	■	+	■■■			■	■		■■■
162.7	■■■■	+	■■■■■	■	+	■■■		■	+	+		■■■■■
162.8	+	+	■■■	■	■	■■■		■■		+		■■■■
022	+	+	■	+	■	+				+		■■

+ present in trace amounts; ■ (<2%); ■■ (2-5%); ■■■ (5-10%); ■■■■ (10-20%); ■■■■■ (20-30%); ■■■■■■ (30-40%); ■■■■■■■ (40-50%); ■■■■■■■■ (50-60%); ■■■■■■■■■ (60-70%); ■■■■■■■■■■ (>70%) (following Bullock et al. 1985)
* frequency class for voids refers to % of total void space (following Stoops 2021: 73, section 5.2.4.)

Supplementary Material 1; Table 11.2 GS16-K: Thin-section interpretation



Context	Summary of key features	Interpretation
162.5	Similar to 162.3 in GS16-J. Orange, compact sandy silt loam with almost all fine material rubified by heating. Contains limited amorphous organic matter and no anthropogenic inclusions other than very limited charred amorphous material. Appears lighter in colour at 1:1 scale than 162.3 due to the thinner nature of the slide and a loss of material during manufacturing.	Heat-affected, organic-deficient soil with evidence of digging. Likely represents a B or AB horizon in an inverted turf. Deposited during construction of turf stack (e.g. wall or internal feature).
162.6	Sandy silt loam with spongy and crumb microstructure, extensive organic acid pigmentation and occasional Fe nodules. Increased amount of charred wood and amorphous organic matter towards bottom of layer. Subangular stone inclusions (up to 11 x 6 mm) account for around 5% of what was captured in thin-section and were similarly concentrated towards the bottom of the layer.	Bioturbated soil that likely represents an A horizon in an inverted turf. Deposited during construction of turf stack (e.g. wall or internal feature).
162.7	Similar to 162.4 in GS16-J. Extremely organic layer, primarily composed of charred and partially-charred wood and charred amorphous organic matter, with very little soil. Charring is less complete than in 162.4, with less rubified fine material. Bioturbation and excremental pedofeatures are more extensive in this layer than in 162.4 (likely due to the less-complete charring of organic material). As in 162.4, identifiable charcoal appears to be largely deciduous, most likely from the birch/willow family. Presence of intrusive soil aggregates (spongy; yellowish-brown; dotted) are similar to the natural subsoil (022).	Bioturbated organic layer with evidence of digging and almost no soil component. Likely represents a burnt O horizon in an inverted turf. Deposited during construction of turf stack (e.g. wall or internal feature).
162.8	Sandy silt loam with spongy and crumb microstructure, intrusive soil aggregates (likely 022) and organic acid pigmentation. Contains small to medium earthworm channels partially filled with amorphous charred material from layer 162.5 above (excluded from quantification).	Bioturbated soil whose structure is typical of A or compacted A horizon. May represent the original ground surface which has been truncated.
022	Compact sandy loam with very limited amorphous organic matter. No anthropogenic inclusions other than limited charred amorphous organic matter and charcoal. Root and earthworm channels have introduced material from the layers above. Subangular stones (up to 5 x 6 mm) account for around 10% of the layer.	Non-sterile glacial subsoil (disturbed with partially-infilled earthworm channels, modern roots and small fragments of charcoal).

SM2: Microrefuse, geochemical, magnetic, multi-element and statistical data

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Sheet 1: Grid coordinates, geochemical, magnetic and microrefuse data

Grid	POINT X	POINT Y	pH	EC	LOI	Mag sus	Charcoal	Burnt bone
A1	313912.2677	763767.0716	4.1	298	13.2	37.9	0	0
A2	313912.7572	763767.2436	4.0	323	13.1	58.5	4	0
A3	313913.207	763767.4156	3.8	292	13.8	49.6	0	0
A4	313913.7097	763767.5875	3.6	321	8.9	75.2	4	0
A5	313914.1595	763767.7463	3.6	417	8.6	94.2	9	0
A6	313914.6357	763767.9315	3.8	587	12.3	106.4	7	0
A7	313915.0855	763768.0902	3.6	436	9.3	87.0	0	0
A8	313915.5485	763768.2755	3.9	251	8.3	91.8	0	0
A9	313916.0116	763768.4342	3.7	429	11.5	97.3	0	0
A10	313916.4746	763768.6062	3.4	622	21.0	65.8	12	0
A11	313916.9773	763768.7782	3.6	705	20.9	99.3	2	0
A12	313917.4271	763768.9501	3.4	692	15.7	158.8	20	2
A13	313917.8372	763769.0957	4.7	99	17.3	219.1	2	0
B1	313912.0799	763767.5584	4.0	340	15.8	30.1	0	0
B2	313912.5773	763767.7278	4.5	222	12.7	50.8	0	0
B3	313913.0324	763767.8865	4.0	222	9.3	61.1	0	0
B4	313913.5192	763768.077	3.8	364	14.2	77.3	0	0
B5	313913.9954	763768.2464	3.9	352	9.2	85.2	0	0
B6	313914.4505	763768.4157	3.7	328	7.9	87.5	4	0
B7	313914.9162	763768.585	3.8	331	8.7	103.5	0	0
B8	313915.3607	763768.7544	4.0	343	8.4	112.2	3	1
B9	313915.8369	763768.9237	3.8	376	10.3	143.2	7	0
B11	313916.7894	763769.2835	3.7	332	8.7	79.5	3	0
B12	313917.2551	763769.4423	3.4	793	12.9	73.9	0	0
B13	313917.6679	763769.5904	3.9	154	12.6	124.8	20	0
C1	313911.9066	763768.0545	4.3	189	17.5	26.8	0	0
C2	313912.404	763768.2239	3.8	236	12.5	51.4	0	0
C3	313912.8485	763768.3932	4.0	335	10.8	113.9	2	0
C7	313914.7217	763769.0811	3.9	251	8.4	124.9	7	0
C8	313915.1874	763769.2504	4.1	465	8.8	170.9	11	0
C11	313916.6161	763769.769	3.8	515	13.1	140.9	12	2
C12	313917.0818	763769.9384	3.8	457	12.6	224.5	5	0

C13	313917.4946	763770.0865	3.8	279	15.5	93.9	10	0
D1	313911.7372	763768.5308	3.9	292	11.8	39.2	0	0
D2	313912.2241	763768.7001	3.9	517	16.5	63.6	0	0
D3	313912.6686	763768.8694	3.9	393	13.0	104.6	0	0
D4	313913.166	763769.0494	3.7	455	14.2	91.2	0	0
D8	313915.0181	763769.7161	3.7	211	6.0	194.4	12	0
D9	313915.4837	763769.8854	3.7	329	7.1	110.1	19	0
D10	313915.9494	763770.0654	4.0	426	9.1	87.0	0	0
D11	313916.4362	763770.2453	3.5	434	11.2	112.5	20	0
D12	313916.9019	763770.4146	3.7	437	13.2	118.9	0	0
D13	313917.3464	763770.5734	3.9	482	17.5	71.6	0	0
E1	313911.5573	763768.9753	3.8	701	13.4	67.5	5	0
E2	313912.0547	763769.1552	4.3	363	13.0	93.7	0	0
E3	313912.5098	763769.3245	3.9	386	10.8	100.8	0	0
E4	313913.0072	763769.4939	3.8	318	9.2	83.5	8	0
E5	313913.4729	763769.6738	3.4	773	14.5	75.5	7	0
E8	313914.8487	763770.1924	4.0	263	5.8	76.6	6	0
E9	313915.3144	763770.3511	3.7	358	6.8	73.8	0	0
E10	313915.7906	763770.5099	3.9	461	9.9	90.1	0	0
E11	313916.2669	763770.7109	3.8	514	17.0	152.0	5	0
E12	313916.7431	763770.8697	3.5	485	11.6	101.0	0	0
E13	313917.1771	763771.0284	3.7	307	12.6	91.6	7	0
F1	313911.388	763769.4674	3.8	310	12.2	57.7	0	0
F2	313911.8854	763769.6473	3.8	259	10.6	77.2	0	0
F3	313912.3299	763769.8167	3.6	344	12.7	116.4	17	0
F4	313912.8167	763769.986	3.4	835	12.7	115.1	18	0
F5	313913.2824	763770.1553	3.8	879	14.1	95.0	5	0
F8	313914.6688	763770.6633	4.0	200	4.7	44.9	0	0
F9	313915.1451	763770.8432	4.3	161	6.0	53.1	0	0
F11	313916.0976	763771.2031	3.5	351	8.2	60.3	10	1
F12	313916.5526	763771.3618	3.7	605	16.1	53.0	30	0
F13	313916.9971	763771.5206	3.8	451	16.5	85.1	0	0
G4	313912.6514	763770.4741	3.6	630	15.0	76.6	0	0
G5	313913.117	763770.6435	3.4	900	15.6	84.4	16	0
G6	313913.5721	763770.8128	3.6	807	12.1	100.3	10	0
H4	313912.4714	763770.9504	3.9	515	17.4	57.2	2	0
H5	313912.9477	763771.1303	3.3	627	19.3	67.4	0	0
H6	313913.4028	763771.2996	3.4	463	15.8	86.2	3	0
K11	313915.1914	763773.6756	3.6	458	11.3	284.0	56	0

K12	313915.657	763773.8344	3.6	717	12.3	320.0	8	0
K13	313916.1439	763774.0143	3.6	745	13.3	264.9	2	4
K14	313916.6201	763774.1836	3.4	602	12.5	365.8	22	0
K15	313917.1069	763774.3635	3.4	628	12.4	254.8	20	0
K16	313917.6202	763774.554	3.5	844	12.9	262.1	0	0
K17	313918.1071	763774.7234	3.5	689	12.0	344.1	4	2
K18	313918.5833	763774.9033	3.5	636	10.8	372.0	24	0
K19	313919.0596	763775.0726	3.7	505	10.2	345.7	17	0
K20	313919.6099	763775.2843	3.6	441	9.7	365.2	42	4
K21	313920.0756	763775.4536	4.0	286	8.1	375.4	29	2
K22	313920.5942	763775.6441	3.8	225	5.9	301.4	7	1
K23	313921.0598	763775.8029	3.6	446	7.6	239.5	12	0
L11	313915.0167	763774.1624	3.5	724	12.8	189.8	26	0
L12	313915.4824	763774.3318	3.5	670	11.4	265.5	12	2
L13	313915.9798	763774.5011	3.6	786	13.7	209.2	0	0
L14	313916.4561	763774.681	3.6	583	10.7	310.0	13	0
L15	313916.9323	763774.8609	3.7	360	10.2	362.3	22	0
L16	313917.4403	763775.0409	3.6	510	11.8	277.9	20	0
L17	313917.9272	763775.2208	3.6	571	10.6	270.3	22	2
L18	313918.4193	763775.3954	3.7	346	10.1	286.1	32	2
L19	313918.885	763775.5753	3.3	394	10.7	415.2	38	0
L20	313919.4141	763775.7658	3.4	400	10.5	490.1	27	2
L21	313919.9115	763775.9352	3.7	369	9.4	546.3	33	0
L22	313920.409	763776.1362	3.8	330	10.3	446.4	100	2
M12	313915.3078	763774.8027	3.7	743	11.6	246.8	10	10
M13	313915.7946	763774.9721	3.5	678	11.8	268.2	0	0
M14	313916.2709	763775.1626	3.8	620	11.3	306.7	6	0
M15	313916.7471	763775.3425	3.8	591	11.5	379.8	63	0
M19	313918.705	763776.041	3.6	447	9.0	291.0	18	0
M20	313919.2607	763776.2474	3.3	402	9.4	426.2	38	0
M21	313919.7157	763776.4167	3.7	400	9.6	522.8	96	0
M22	313920.2343	763776.5966	3.7	260	9.8	588.4	84	7
M23	313920.7106	763776.766	3.8	455	11.3	469.3	44	0
M24	313921.1868	763776.9565	3.3	611	15.9	419.3	31	0
M25	313921.6419	763777.1152	3.6	756	17.0	310.6	8	0
M26	313922.1182	763777.2951	3.6	598	14.0	286.6	104	0
M27	313922.6156	763777.475	3.5	775	17.2	203.5	26	0
M28	313923.0813	763777.655	3.8	604	15.1	116.8	7	0
N1	313909.9473	763773.3899	3.6	859	16.5	56.1	0	0

N2	313910.4341	763773.5592	3.6	658	17.2	58.2	0	0
N3	313910.9104	763773.7497	3.8	607	16.7	64.1	5	0
N4	313911.3972	763773.9084	3.8	634	21.6	68.2	26	0
N5	313911.8629	763774.0884	3.5	462	22.9	113.7	0	0
N6	313912.318	763774.2577	3.5	391	16.3	91.0	8	0
N7	313912.7836	763774.427	3.7	134	18.2	64.6	0	0
N8	313913.2493	763774.5964	3.7	307	15.7	208.7	20	0
N9	313913.7044	763774.7551	3.9	518	17.0	165.8	18	0
N10	313914.1806	763774.935	3.8	472	17.8	84.5	16	0
N13	313915.6306	763775.4642	3.4	793	12.9	323.5	24	0
N14	313916.0962	763775.6335	3.5	757	11.8	380.5	28	0
N15	313916.5725	763775.8134	3.6	570	11.6	431.0	25	0
N19	313918.5304	763776.5331	3.8	234	9.6	455.1	133	0
N20	313919.0702	763776.7236	4.2	575	10.1	481.0	58	2
N21	313919.5358	763776.9035	3.7	617	10.3	552.0	82	0
N22	313920.065	763777.0835	3.6	393	10.7	609.6	110	6
N23	313920.5307	763777.2528	3.6	336	11.9	666.6	100	1
N24	313921.0069	763777.4327	3.7	546	14.2	359.5	68	0
N25	313921.4726	763777.602	3.7	508	15.4	381.2	49	0
N26	313921.9488	763777.7714	3.5	562	13.7	258.5	22	0
N27	313922.4357	763777.9619	3.5	432	12.5	176.1	20	0
N28	313922.9119	763778.1418	3.7	251	9.3	177.5	5	0
O1	313909.7727	763773.8926	3.4	994	15.3	103.5	0	0
O2	313910.2595	763774.0725	3.5	643	18.6	90.3	0	0
O3	313910.7252	763774.2418	3.2	783	18.2	91.8	0	0
O4	313911.2014	763774.4217	3.5	988	19.4	39.2	6	0
O5	313911.6777	763774.5805	3.4	533	22.7	82.3	13	0
O6	313912.1434	763774.771	3.5	350	13.7	42.5	22	0
O7	313912.5984	763774.9297	4.0	166	14.7	123.3	0	0
O8	313913.0535	763775.0885	4.2	305	13.6	164.1	15	0
O9	313913.5192	763775.2684	3.6	506	13.7	136.8	0	0
O10	313913.9954	763775.4272	3.6	353	13.8	256.1	22	0
O13	313915.4348	763775.9563	3.5	692	12.9	348.3	51	0
O14	313915.9322	763776.1468	3.2	662	14.0	485.3	34	0
O15	313916.3873	763776.3056	3.3	671	13.6	486.2	4	0
O16	313916.9059	763776.5067	3.5	550	11.7	337.0	23	0
O17	313917.4033	763776.676	3.5	652	12.2	345.6	15	0
O18	313917.8689	763776.8347	3.6	489	11.7	387.8	14	0
O19	313918.3769	763777.0252	3.5	760	13.2	401.5	18	0

O20	313918.8744	763777.2157	3.4	866	14.0	523.0	20	0
O21	313919.3612	763777.3957	3.4	328	11.5	853.5	100	0
O22	313919.8692	763777.565	3.4	646	12.3	609.2	71	0
O23	313920.3349	763777.7555	3.7	703	14.6	542.5	17	0
O24	313920.8217	763777.9248	3.3	762	14.4	283.9	12	0
O25	313921.298	763778.0942	3.4	692	12.8	127.6	20	0
P1	313909.6033	763774.3794	3.8	604	12.7	79.4	0	0
P2	313910.0902	763774.5487	3.5	663	17.6	66.0	2	0
P3	313910.5453	763774.7287	3.5	847	16.1	87.3	0	0
P4	313911.0427	763774.898	3.5	763	20.7	81.1	0	0
P5	313911.5189	763775.0779	3.6	1069	27.4	28.3	14	0
P6	313911.974	763775.2472	3.5	465	12.1	45.3	0	0
P7	313912.4185	763775.3954	4.0	161	13.5	64.4	0	0
P8	313912.8842	763775.5647	4.3	145	19.1	42.9	0	0
P9	313913.3499	763775.7552	3.7	690	15.8	322.0	27	0
P10	313913.8155	763775.914	4.0	737	15.6	435.0	69	0
P11	313914.3024	763776.0939	3.8	554	14.0	401.3	8	0
P12	313914.7786	763776.2632	3.3	273	12.4	450.9	100	0
P13	313915.276	763776.4537	3.4	535	13.9	667.8	58	0
P14	313915.7417	763776.6231	3.5	361	13.1	191.4	36	0
P15	313916.2285	763776.803	3.6	321	13.9	379.1	32	0
P16	313916.7365	763776.9935	3.6	474	13.5	346.6	31	0
P17	313917.2128	763777.1734	3.8	314	10.5	282.6	11	0
P18	313917.7102	763777.3322	3.4	572	11.5	380.3	38	0
P19	313918.1759	763777.5015	3.4	747	12.8	495.1	23	0
P20	313918.7156	763777.692	3.3	774	12.8	448.9	17	0
P21	313919.1919	763777.8719	3.5	457	10.4	319.9	8	0
P22	313919.7052	763778.0624	3.5	423	11.3	439.9	53	0
P23	313920.1708	763778.2317	3.4	575	10.8	335.8	23	0
P24	313920.6365	763778.4011	3.4	674	11.2	238.6	8	0
P25	313921.1022	763778.5598	3.6	720	11.5	263.5	40	0

Statistics	pH	EC	LOI	Mag sus	Charcoal	Burnt bone
Mean	3.7	502.4	12.9	219.0	18.6	0.3
Median	3.6	473.0	12.7	147.6	10.0	0.0
SE	0.02	14.85	0.26	12.48	1.91	0.09
SD	0.24	199.18	3.52	167.39	25.58	1.17
Max	4.7	1069.0	27.4	853.5	132.5	10.0
Min	3.2	99.0	4.7	26.8	0.0	0.0

Sheet 2: Multi-element data

Grid	Al	Ba	Ca	Cr	Fe	K	Mn	P	Rb	S	Si	Sr	Ti	V	Zn	Zr
A1	6.4280	0.0478	0.5232	0.0128	4.4748	1.9004	0.0406	0.2558	0.0084	0.1024	20.0760	0.0122	0.6398	0.0122	0.0052	0.0228
A2	6.6062	0.0504	0.5886	0.0112	4.3434	1.9548	0.0436	0.2052	0.0094	0.1020	22.0946	0.0126	0.6246	0.0114	0.0058	0.0236
A3	6.6518	0.0460	0.5324	0.0166	5.0830	1.9418	0.0288	0.2198	0.0082	0.0870	20.6316	0.0124	0.6360	0.0114	0.0046	0.0228
A4	8.1340	0.0564	0.5676	0.0172	4.7396	2.1710	0.0548	0.2586	0.0110	0.0788	23.1628	0.0138	0.6982	0.0140	0.0068	0.0280
A5	8.4332	0.0588	0.5754	0.0144	4.7054	2.2216	0.0824	0.2924	0.0108	0.0718	23.4148	0.0132	0.7074	0.0136	0.0078	0.0278
A6	7.2744	0.0516	0.5556	0.0118	4.3074	2.0484	0.0878	0.3204	0.0100	0.0994	21.7196	0.0126	0.6514	0.0130	0.0084	0.0258
A7	8.3198	0.0538	0.5840	0.0140	4.8728	2.2166	0.0958	0.3254	0.0118	0.0822	22.5768	0.0136	0.7198	0.0140	0.0078	0.0270
A8	8.4044	0.0630	0.5674	0.0160	4.9612	2.2240	0.0744	0.2788	0.0124	0.0722	22.6390	0.0136	0.7530	0.0144	0.0076	0.0268
A9	7.9268	0.0570	0.5370	0.0150	5.2438	2.1090	0.0394	0.3470	0.0108	0.0980	21.4278	0.0130	0.6932	0.0126	0.0078	0.0264
A10	6.1286	0.0438	0.4608	0.0150	5.2266	1.7906	0.0214	0.4636	0.0092	0.1554	17.5214	0.0114	0.6084	0.0118	0.0046	0.0216
A11	6.3708	0.0424	0.4764	0.0122	5.0348	1.7612	0.0388	0.2736	0.0088	0.1352	19.3264	0.0110	0.6518	0.0114	0.0050	0.0242
A12	6.8426	0.0470	0.5488	0.0144	4.5762	1.8892	0.0832	0.2882	0.0092	0.1162	21.4076	0.0120	0.6686	0.0132	0.0056	0.0248
A13	6.3486	0.0452	0.5228	0.0150	4.6292	1.8940	0.0310	0.3188	0.0094	0.1146	20.2114	0.0120	0.6964	0.0132	0.0060	0.0232
B1	6.8656	0.0470	0.5306	0.0128	4.9950	1.9852	0.0190	0.2352	0.0080	0.1214	19.3126	0.0118	0.6452	0.0130	0.0044	0.0232
B2	7.4834	0.0482	0.5680	0.0138	4.9686	1.9780	0.0422	0.2104	0.0084	0.1082	22.0032	0.0128	0.6642	0.0146	0.0056	0.0240
B3	8.2582	0.0538	0.5784	0.0142	4.6300	2.1214	0.0380	0.2212	0.0080	0.0730	22.9052	0.0140	0.6932	0.0138	0.0050	0.0240
B4	7.0660	0.0484	0.5472	0.0148	4.7884	1.9086	0.0432	0.2470	0.0090	0.0994	21.6022	0.0124	0.6804	0.0130	0.0056	0.0252
B5	8.6088	0.0572	0.5724	0.0142	5.0978	2.1338	0.1278	0.3038	0.0112	0.0876	23.3186	0.0140	0.7018	0.0136	0.0088	0.0290
B6	8.8428	0.0576	0.5832	0.0128	4.5820	2.2716	0.0926	0.3684	0.0118	0.0678	24.4442	0.0138	0.6960	0.0150	0.0082	0.0266
B7	8.1942	0.0582	0.5596	0.0164	4.9616	2.1790	0.0830	0.3314	0.0116	0.0838	21.9802	0.0128	0.7260	0.0152	0.0088	0.0256
B8	8.9820	0.0560	0.5478	0.0158	5.3294	2.2240	0.1598	0.3638	0.0112	0.0716	22.5672	0.0134	0.6968	0.0152	0.0094	0.0262
B9	8.4486	0.0590	0.5734	0.0134	4.9888	2.0500	0.1026	0.3894	0.0106	0.0896	22.0872	0.0138	0.6888	0.0144	0.0094	0.0270
B11	9.0440	0.0686	0.5574	0.0170	5.9380	2.2394	0.1504	0.4958	0.0106	0.0900	21.3630	0.0154	0.7456	0.0158	0.0136	0.0262
B12	7.3408	0.0518	0.5994	0.0150	4.8096	2.0336	0.1004	0.4058	0.0102	0.1254	21.9440	0.0140	0.6846	0.0156	0.0104	0.0252
B13	7.7506	0.0472	0.5498	0.0158	4.8322	2.0330	0.0492	0.3666	0.0088	0.0900	22.4628	0.0134	0.6536	0.0120	0.0052	0.0222
C1	6.3454	0.0436	0.5718	0.0142	4.3160	1.7890	0.0190	0.1830	0.0076	0.1262	21.6020	0.0118	0.6004	0.0120	0.0038	0.0210
C2	7.6714	0.0480	0.5362	0.0136	5.5326	1.9494	0.0278	0.2154	0.0076	0.1016	20.9682	0.0122	0.6746	0.0134	0.0052	0.0238
C3	7.8340	0.0516	0.5574	0.0128	4.7330	1.9942	0.0554	0.2812	0.0098	0.0914	22.5866	0.0124	0.6770	0.0146	0.0074	0.0260
C7	8.6996	0.0634	0.5712	0.0158	4.8610	2.2056	0.1236	0.3288	0.0116	0.0788	23.4668	0.0138	0.7260	0.0142	0.0104	0.0286
C8	8.9430	0.0642	0.5800	0.0136	4.7638	2.2106	0.1420	0.2942	0.0106	0.0816	23.8936	0.0138	0.6884	0.0126	0.0132	0.0280
C11	7.5458	0.0510	0.5488	0.0164	4.6330	2.0052	0.1716	0.3786	0.0094	0.1170	22.4936	0.0122	0.6546	0.0122	0.0086	0.0246
C12	7.7132	0.0530	0.5958	0.0150	4.6196	2.0222	0.1018	0.2840	0.0102	0.1118	22.7766	0.0128	0.6736	0.0128	0.0068	0.0256
C13	6.5690	0.0422	0.5298	0.0116	4.8484	1.8714	0.0170	0.2810	0.0090	0.1010	21.0466	0.0118	0.6318	0.0150	0.0044	0.0240
D1	6.6486	0.0494	0.5414	0.0134	5.0804	1.8774	0.0292	0.1784	0.0076	0.0944	20.9218	0.0128	0.6288	0.0148	0.0044	0.0234
D2	6.2098	0.0440	0.5338	0.0140	4.3394	1.8086	0.0334	0.2074	0.0080	0.1096	20.9292	0.0120	0.6114	0.0114	0.0044	0.0238

D3	6.9882	0.0480	0.5706	0.0134	4.5614	1.9128	0.0412	0.2460	0.0084	0.0866	21.7780	0.0132	0.6466	0.0112	0.0050	0.0262
D4	6.5252	0.0478	0.5144	0.0134	4.5746	1.9260	0.0316	0.2334	0.0086	0.0958	21.2780	0.0122	0.6714	0.0140	0.0046	0.0252
D8	9.4070	0.0740	0.6592	0.0154	4.6994	2.3536	0.1758	0.2760	0.0086	0.0476	24.6330	0.0146	0.6628	0.0140	0.0176	0.0262
D9	9.1704	0.0646	0.6778	0.0118	4.7496	2.2184	0.1634	0.3548	0.0094	0.0602	23.8396	0.0136	0.6820	0.0118	0.0126	0.0278
D10	8.2920	0.0650	0.5288	0.0182	5.1344	2.1036	0.1132	0.4354	0.0096	0.0830	21.0606	0.0132	0.6336	0.0140	0.0118	0.0244
D11	7.7540	0.0546	0.5958	0.0152	4.9794	1.9508	0.1236	0.3644	0.0086	0.0962	22.2280	0.0140	0.6842	0.0140	0.0104	0.0238
D12	7.3640	0.0500	0.5592	0.0140	4.4900	1.9200	0.0382	0.2222	0.0086	0.0840	23.0768	0.0132	0.6996	0.0150	0.0048	0.0250
D13	6.4948	0.0418	0.5560	0.0112	3.8158	1.9232	0.0152	0.2732	0.0088	0.1152	21.9234	0.0120	0.6746	0.0136	0.0042	0.0264
E1	7.7450	0.0462	0.6140	0.0140	4.6494	2.0874	0.0434	0.2470	0.0086	0.1134	22.2668	0.0124	0.6378	0.0124	0.0058	0.0240
E2	7.5900	0.0532	0.6314	0.0120	4.6494	2.0012	0.0458	0.2740	0.0088	0.1014	23.1520	0.0128	0.6486	0.0122	0.0070	0.0218
E3	8.3294	0.0506	0.6148	0.0118	4.7972	2.0696	0.1246	0.2994	0.0096	0.0924	23.5470	0.0128	0.6856	0.0132	0.0090	0.0258
E4	8.0274	0.0530	0.6294	0.0134	5.0568	2.1034	0.0608	0.3580	0.0100	0.0848	22.4968	0.0148	0.7176	0.0152	0.0086	0.0268
E5	7.3512	0.0502	0.5446	0.0126	4.5266	2.1326	0.0734	0.2848	0.0090	0.1008	21.8398	0.0126	0.6740	0.0106	0.0058	0.0264
E8	10.2622	0.0686	0.6084	0.0132	4.9278	2.4864	0.1238	0.2856	0.0112	0.0526	24.4878	0.0150	0.7514	0.0152	0.0140	0.0280
E9	9.7464	0.0664	0.6390	0.0158	4.8670	2.4446	0.0804	0.2478	0.0102	0.0596	24.3032	0.0136	0.7156	0.0144	0.0128	0.0298
E10	8.9408	0.0648	0.6156	0.0168	5.4466	2.2002	0.0896	0.3466	0.0102	0.0916	22.4752	0.0138	0.7028	0.0154	0.0126	0.0276
E11	7.0474	0.0462	0.5010	0.0146	4.5626	1.7862	0.1890	0.3698	0.0080	0.1102	20.2824	0.0114	0.6454	0.0120	0.0076	0.0240
E12	7.8986	0.0522	0.6204	0.0122	4.3618	2.0280	0.0386	0.2346	0.0092	0.0816	23.8188	0.0138	0.7472	0.0146	0.0052	0.0276
E13	7.6288	0.0460	0.5606	0.0136	4.6048	1.9692	0.0284	0.2770	0.0084	0.0976	22.8180	0.0126	0.7052	0.0134	0.0054	0.0260
F1	7.9058	0.0486	0.5602	0.0126	5.0506	2.0606	0.0262	0.2208	0.0080	0.1016	21.3226	0.0124	0.6732	0.0132	0.0046	0.0250
F2	8.0456	0.0492	0.5918	0.0142	4.8358	1.9798	0.0364	0.2334	0.0084	0.0838	23.0726	0.0134	0.6790	0.0160	0.0058	0.0250
F3	7.6200	0.0442	0.5720	0.0142	4.9392	1.9912	0.1266	0.2768	0.0086	0.0888	21.8086	0.0128	0.6590	0.0120	0.0062	0.0224
F4	7.6218	0.0494	0.5860	0.0120	4.8342	2.0336	0.0900	0.4138	0.0088	0.1094	21.9218	0.0132	0.6592	0.0126	0.0066	0.0268
F5	7.3640	0.0510	0.6002	0.0150	4.5928	2.0146	0.0920	0.3680	0.0090	0.1202	22.0764	0.0140	0.6584	0.0142	0.0080	0.0252
F8	10.3592	0.0728	0.7182	0.0152	5.0692	2.4220	0.0826	0.2892	0.0090	0.0428	25.5906	0.0150	0.6618	0.0138	0.0134	0.0250
F9	9.8792	0.0692	0.6836	0.0128	5.0660	2.2848	0.0602	0.4928	0.0086	0.0480	24.1978	0.0146	0.6570	0.0136	0.0106	0.0286
F11	8.8976	0.0622	0.6224	0.0140	5.0722	2.0688	0.0574	0.4044	0.0102	0.0686	23.5194	0.0140	0.6580	0.0144	0.0096	0.0248
F12	6.9874	0.0524	0.4824	0.0140	4.8078	1.9348	0.1868	0.4310	0.0100	0.1252	19.9656	0.0116	0.6430	0.0148	0.0060	0.0244
F13	6.7768	0.0494	0.5272	0.0152	4.7410	1.8474	0.0892	0.3422	0.0084	0.1130	20.3044	0.0116	0.6474	0.0140	0.0058	0.0220
G4	6.0790	0.0474	0.6154	0.0118	3.9620	1.7392	0.0644	0.3746	0.0082	0.1100	21.6134	0.0124	0.6024	0.0106	0.0066	0.0240
G5	6.4854	0.0390	0.5752	0.0114	4.1416	1.8626	0.0826	0.3900	0.0088	0.1234	20.9774	0.0120	0.6080	0.0130	0.0074	0.0238
G6	7.2996	0.0532	0.6138	0.0128	4.3914	1.9504	0.0796	0.3242	0.0076	0.0888	22.7496	0.0130	0.6066	0.0128	0.0074	0.0230
H4	6.0374	0.0444	0.5382	0.0118	4.4290	1.6482	0.0354	0.4232	0.0072	0.1186	20.4302	0.0110	0.5884	0.0120	0.0042	0.0214
H5	6.0388	0.0408	0.5274	0.0148	4.2802	1.6930	0.0258	0.3876	0.0070	0.1362	20.3752	0.0112	0.6246	0.0112	0.0046	0.0244
H6	6.6108	0.0454	0.5152	0.0132	4.3380	1.7634	0.0222	0.3160	0.0074	0.1056	21.8040	0.0116	0.6538	0.0116	0.0042	0.0250
K11	7.6788	0.0584	0.6058	0.0130	4.3100	1.9610	0.1572	0.3276	0.0096	0.1056	22.3798	0.0142	0.6538	0.0130	0.0122	0.0256
K12	7.8238	0.0498	0.5648	0.0132	4.2420	1.9726	0.1702	0.3216	0.0094	0.1022	23.2098	0.0124	0.6984	0.0122	0.0136	0.0262
K13	7.0496	0.0556	0.5570	0.0128	4.1778	1.8584	0.1336	0.2764	0.0096	0.1164	22.4178	0.0124	0.6370	0.0128	0.0100	0.0248
K14	7.7290	0.0540	0.5514	0.0152	4.5968	1.9616	0.2746	0.2938	0.0096	0.0980	22.8770	0.0136	0.6626	0.0130	0.0128	0.0270

K15	7.7592	0.0488	0.5874	0.0128	4.6132	1.8728	0.1070	0.2564	0.0086	0.0988	22.9798	0.0134	0.6832	0.0132	0.0106	0.0248
K16	7.4626	0.0518	0.5926	0.0132	4.3854	1.9054	0.1134	0.2492	0.0090	0.1018	23.7584	0.0128	0.6506	0.0140	0.0116	0.0240
K17	7.9896	0.0544	0.6156	0.0126	4.5030	1.9250	0.1328	0.3322	0.0100	0.1066	22.7780	0.0138	0.6520	0.0142	0.0118	0.0262
K18	7.8786	0.0520	0.5692	0.0124	4.6246	1.9148	0.1314	0.2782	0.0090	0.1004	22.6484	0.0128	0.6442	0.0132	0.0116	0.0240
K19	7.8296	0.0498	0.5806	0.0112	4.5450	1.9158	0.1806	0.2776	0.0094	0.0952	22.6636	0.0132	0.6510	0.0152	0.0124	0.0242
K20	8.5394	0.0528	0.5866	0.0130	4.8380	2.0040	0.1958	0.3000	0.0086	0.0984	22.9376	0.0128	0.7184	0.0136	0.0140	0.0250
K21	9.1546	0.0652	0.6142	0.0124	4.5612	2.1262	0.1900	0.2898	0.0086	0.0740	25.2678	0.0132	0.6910	0.0146	0.0142	0.0252
K22	9.5902	0.0584	0.6330	0.0130	4.5930	2.2570	0.1670	0.2534	0.0092	0.0496	25.7516	0.0134	0.7126	0.0124	0.0128	0.0270
K23	9.1966	0.0642	0.6430	0.0138	4.5278	2.1662	0.1346	0.1994	0.0100	0.0630	24.5792	0.0142	0.6998	0.0134	0.0122	0.0282
L11	7.7296	0.0504	0.6010	0.0128	4.2310	1.9392	0.1548	0.3240	0.0092	0.1006	23.8258	0.0120	0.6396	0.0126	0.0106	0.0242
L12	7.9200	0.0508	0.5890	0.0116	4.3900	1.9918	0.1368	0.2894	0.0098	0.1012	23.2374	0.0130	0.6868	0.0128	0.0112	0.0264
L13	7.6164	0.0506	0.5516	0.0112	4.3722	1.9266	0.1506	0.2700	0.0100	0.1142	23.4994	0.0124	0.6444	0.0116	0.0108	0.0258
L14	8.4332	0.0550	0.5650	0.0124	4.6454	2.0414	0.1930	0.2376	0.0098	0.0896	23.4370	0.0136	0.6774	0.0134	0.0134	0.0256
L15	8.3284	0.0522	0.5814	0.0128	4.5476	1.9682	0.1740	0.2480	0.0086	0.0844	23.7848	0.0130	0.6860	0.0158	0.0132	0.0282
L16	8.4790	0.0484	0.5796	0.0132	4.6298	2.0250	0.1262	0.2586	0.0090	0.1012	23.4206	0.0132	0.6792	0.0140	0.0120	0.0256
L17	8.4512	0.0546	0.5532	0.0134	4.7040	2.0342	0.1246	0.2818	0.0094	0.0944	22.4000	0.0140	0.6760	0.0134	0.0148	0.0262
L18	8.3994	0.0588	0.6136	0.0122	4.6488	1.9270	0.1758	0.2904	0.0086	0.0978	23.5570	0.0152	0.6636	0.0132	0.0152	0.0264
L19	8.3946	0.0536	0.5966	0.0130	4.6344	1.9476	0.2010	0.2966	0.0090	0.1028	23.1802	0.0134	0.6542	0.0124	0.0152	0.0252
L20	8.1526	0.0570	0.5526	0.0140	4.5812	1.9150	0.2366	0.3008	0.0084	0.0950	23.5754	0.0128	0.6638	0.0132	0.0142	0.0256
L21	8.7322	0.0604	0.5610	0.0134	4.5244	1.9972	0.2936	0.3010	0.0086	0.0888	24.1628	0.0136	0.6840	0.0136	0.0162	0.0268
L22	8.7800	0.0608	0.8402	0.0138	4.5896	1.9084	0.3078	0.3800	0.0088	0.0930	23.6540	0.0134	0.6758	0.0142	0.0154	0.0256
M12	7.2044	0.0544	0.5776	0.0144	4.4184	1.9982	0.1736	0.2298	0.0090	0.0874	21.7414	0.0126	0.6614	0.0112	0.0106	0.0258
M13	7.6560	0.0556	0.5760	0.0120	4.4120	1.9134	0.1788	0.2232	0.0088	0.1296	23.2108	0.0130	0.6804	0.0138	0.0114	0.0256
M14	7.6788	0.0540	0.5672	0.0114	4.5972	2.0282	0.1670	0.2404	0.0096	0.0976	22.8198	0.0138	0.6666	0.0132	0.0122	0.0286
M15	7.5210	0.0548	0.6008	0.0124	4.4646	1.9000	0.2202	0.2694	0.0088	0.0976	22.2202	0.0132	0.6812	0.0150	0.0144	0.0258
M19	8.0572	0.0554	0.5990	0.0136	4.7702	1.8890	0.1616	0.2872	0.0084	0.0936	23.1990	0.0132	0.6988	0.0138	0.0140	0.0224
M20	8.4824	0.0596	0.6134	0.0136	4.5860	1.9178	0.2534	0.3018	0.0082	0.0878	24.4336	0.0136	0.6550	0.0142	0.0164	0.0250
M21	8.3244	0.0578	0.5936	0.0140	4.6758	1.8980	0.3026	0.3418	0.0078	0.0930	23.4780	0.0130	0.6514	0.0132	0.0166	0.0274
M22	8.7658	0.0650	0.6010	0.0128	4.7752	1.9032	0.3208	0.3696	0.0088	0.0796	24.2904	0.0130	0.6894	0.0118	0.0168	0.0292
M23	8.3448	0.0610	0.5624	0.0116	4.4342	2.0140	0.2892	0.3156	0.0098	0.0946	23.2442	0.0126	0.6600	0.0130	0.0146	0.0276
M24	7.6722	0.0510	0.5248	0.0136	4.6024	1.8962	0.2574	0.3020	0.0100	0.1260	22.3416	0.0118	0.6508	0.0124	0.0096	0.0262
M25	6.6980	0.0434	0.5296	0.0134	4.5174	1.7822	0.1344	0.2974	0.0106	0.1312	22.1402	0.0116	0.6124	0.0148	0.0080	0.0260
M26	7.4710	0.0510	0.5450	0.0146	4.4016	2.0152	0.1410	0.4080	0.0112	0.1114	22.8136	0.0126	0.6688	0.0128	0.0078	0.0254
M27	6.8352	0.0536	0.5094	0.0134	4.6750	1.8356	0.1908	0.3366	0.0102	0.1458	21.3106	0.0140	0.6362	0.0120	0.0066	0.0246
M28	7.4524	0.0458	0.5284	0.0146	4.5994	1.9206	0.2564	0.3330	0.0100	0.1316	22.3234	0.0116	0.6378	0.0124	0.0078	0.0236
N1	6.9288	0.0490	0.5614	0.0140	3.9472	1.9788	0.0260	0.2314	0.0098	0.1158	22.3392	0.0122	0.6430	0.0126	0.0058	0.0254
N2	6.5132	0.0454	0.5362	0.0114	4.4612	1.8390	0.0168	0.2746	0.0086	0.1114	21.1238	0.0114	0.6570	0.0126	0.0048	0.0246
N3	6.9076	0.0448	0.5752	0.0136	4.9904	1.8612	0.0218	0.2724	0.0082	0.1130	21.5808	0.0124	0.6512	0.0126	0.0042	0.0254
N4	5.9740	0.0440	0.5642	0.0150	5.1510	1.7012	0.0294	0.3754	0.0082	0.1506	18.1952	0.0118	0.5862	0.0118	0.0056	0.0228

N5	5.9370	0.0396	0.4644	0.0168	5.4062	1.6766	0.0156	0.3014	0.0076	0.1392	18.4388	0.0104	0.6036	0.0120	0.0048	0.0238
N6	6.6840	0.0430	0.5204	0.0126	4.9852	1.9374	0.0184	0.2852	0.0084	0.1232	20.3152	0.0118	0.6660	0.0142	0.0058	0.0254
N7	6.1424	0.0496	0.4818	0.0146	5.4482	1.8262	0.0250	0.2738	0.0078	0.1366	18.8562	0.0122	0.6602	0.0146	0.0058	0.0240
N8	6.7074	0.0394	0.5396	0.0124	4.6298	1.7518	0.0202	0.3482	0.0076	0.1146	20.9544	0.0120	0.6700	0.0136	0.0066	0.0248
N9	6.7636	0.0474	0.5760	0.0120	4.2176	1.8228	0.0760	0.3840	0.0090	0.1178	22.9222	0.0126	0.6164	0.0128	0.0080	0.0234
N10	6.5362	0.0496	0.5332	0.0116	4.1438	1.7758	0.0378	0.3994	0.0082	0.1266	21.4754	0.0120	0.6282	0.0112	0.0060	0.0236
N13	7.7046	0.0464	0.5536	0.0134	4.5586	1.9318	0.1420	0.2722	0.0092	0.1054	22.6184	0.0128	0.6798	0.0124	0.0104	0.0252
N14	8.0602	0.0552	0.5750	0.0116	4.5432	1.9442	0.1910	0.2706	0.0088	0.0984	23.3790	0.0136	0.6896	0.0124	0.0112	0.0254
N15	7.9282	0.0490	0.5790	0.0124	4.5886	1.8876	0.1902	0.2688	0.0086	0.0980	23.2700	0.0130	0.6416	0.0122	0.0130	0.0272
N19	8.6090	0.0530	0.5842	0.0156	4.5572	1.8894	0.3310	0.3424	0.0084	0.1022	22.5840	0.0134	0.6634	0.0156	0.0222	0.0234
N20	7.8976	0.0600	0.7174	0.0138	4.5614	1.7536	0.2904	0.3370	0.0082	0.0784	23.0974	0.0132	0.5970	0.0150	0.0182	0.0250
N21	8.7100	0.0624	0.9854	0.0126	4.7020	1.9936	0.2718	0.5402	0.0086	0.0898	23.4708	0.0130	0.6560	0.0124	0.0180	0.0260
N22	8.8396	0.0668	0.5984	0.0140	4.6468	1.9822	0.3326	0.3588	0.0090	0.0892	23.6174	0.0132	0.6736	0.0150	0.0174	0.0262
N23	8.4422	0.0552	0.5680	0.0150	4.5752	1.9696	0.3100	0.3470	0.0098	0.1004	24.1366	0.0130	0.6858	0.0136	0.0156	0.0322
N24	6.8554	0.0474	0.5154	0.0106	4.4324	1.8434	0.1740	0.2532	0.0098	0.1180	21.6120	0.0120	0.6658	0.0120	0.0104	0.0256
N25	7.3046	0.0422	0.5020	0.0132	4.6020	1.8894	0.2480	0.3378	0.0100	0.1216	20.9042	0.0130	0.6378	0.0128	0.0106	0.0248
N26	7.2162	0.0450	0.5508	0.0118	4.3012	1.8548	0.1686	0.2822	0.0106	0.1026	24.0070	0.0118	0.6612	0.0140	0.0068	0.0264
N27	7.4802	0.0496	0.5332	0.0128	4.6886	1.9688	0.2350	0.3328	0.0096	0.1100	22.4812	0.0118	0.6646	0.0126	0.0070	0.0224
N28	8.1140	0.0544	0.5498	0.0112	4.4102	2.1520	0.2060	0.4196	0.0108	0.0796	23.5774	0.0134	0.7288	0.0128	0.0078	0.0278
O1	7.3888	0.0500	0.5812	0.0132	4.4520	2.0018	0.0606	0.2734	0.0096	0.1136	23.2700	0.0116	0.6112	0.0130	0.0056	0.0240
O2	6.1594	0.0362	0.5278	0.0098	3.5422	1.8416	0.0180	0.2206	0.0090	0.1204	22.4664	0.0112	0.6512	0.0132	0.0032	0.0254
O3	6.1170	0.0408	0.5288	0.0134	4.5554	1.7540	0.0192	0.2474	0.0084	0.1316	20.0848	0.0116	0.6286	0.0126	0.0048	0.0256
O4	6.5188	0.0354	0.6146	0.0156	4.6304	1.8200	0.0480	0.3754	0.0090	0.1410	20.1968	0.0116	0.6346	0.0140	0.0056	0.0250
O5	5.7770	0.0394	0.4548	0.0118	5.3202	1.6956	0.0130	0.3124	0.0076	0.1388	18.5020	0.0104	0.6274	0.0126	0.0044	0.0228
O6	7.2692	0.0506	0.5578	0.0152	5.4298	2.0238	0.0240	0.3062	0.0080	0.1018	21.3704	0.0120	0.6580	0.0148	0.0056	0.0262
O7	6.8738	0.0486	0.4942	0.0170	5.6852	1.9614	0.0248	0.2860	0.0086	0.1248	19.8654	0.0122	0.6796	0.0138	0.0054	0.0248
O8	7.3120	0.0496	0.5334	0.0136	4.9152	1.9390	0.0304	0.2998	0.0080	0.1184	21.8214	0.0132	0.6822	0.0134	0.0064	0.0238
O9	7.0878	0.0452	0.5612	0.0128	4.4152	1.8172	0.0258	0.3246	0.0076	0.0912	23.0206	0.0130	0.6470	0.0126	0.0052	0.0260
O10	7.4734	0.0488	0.5620	0.0146	4.3434	1.9096	0.0340	0.3542	0.0082	0.0950	24.2204	0.0130	0.6558	0.0112	0.0056	0.0236
O13	7.5616	0.0470	0.5880	0.0132	4.5100	1.8964	0.0768	0.3472	0.0080	0.1124	22.8008	0.0122	0.6740	0.0132	0.0086	0.0248
O14	7.6702	0.0396	0.5392	0.0118	4.4668	1.7996	0.0934	0.3152	0.0082	0.1024	23.0878	0.0116	0.6530	0.0128	0.0082	0.0256
O15	7.7440	0.0534	0.5464	0.0162	4.6636	1.8728	0.1120	0.3134	0.0084	0.1066	22.6362	0.0116	0.6374	0.0132	0.0080	0.0258
O16	7.8576	0.0476	0.5908	0.0138	4.3540	1.9112	0.0856	0.2752	0.0094	0.0904	25.4612	0.0140	0.6402	0.0122	0.0088	0.0248
O17	8.3196	0.0496	0.5664	0.0158	4.3678	1.9842	0.1396	0.2912	0.0092	0.1076	23.6748	0.0134	0.6580	0.0130	0.0114	0.0242
O18	8.2610	0.0530	0.6040	0.0152	4.6552	1.9088	0.1528	0.2778	0.0086	0.1046	24.3900	0.0132	0.6416	0.0124	0.0128	0.0242
O19	8.2286	0.0536	0.5900	0.0120	4.4400	1.8560	0.1492	0.2658	0.0092	0.1218	23.8936	0.0130	0.6702	0.0118	0.0112	0.0248
O20	8.1856	0.0570	0.5912	0.0144	4.7232	1.8882	0.2722	0.3066	0.0092	0.1150	23.5122	0.0124	0.6586	0.0152	0.0120	0.0252
O21	8.1982	0.0576	0.5340	0.0158	4.8322	1.7746	0.4134	0.3638	0.0090	0.1046	22.3716	0.0130	0.6398	0.0118	0.0154	0.0236
O22	8.0318	0.0570	0.5604	0.0174	4.3936	1.9930	0.2142	0.2646	0.0098	0.0970	23.2284	0.0124	0.6944	0.0146	0.0126	0.0266

O23	7.3424	0.0508	0.5774	0.0142	4.1912	1.8214	0.1756	0.2760	0.0098	0.1202	23.7366	0.0122	0.6550	0.0110	0.0094	0.0254
O24	8.0584	0.0510	0.5862	0.0120	4.0128	1.9206	0.1004	0.2658	0.0092	0.1154	25.2882	0.0130	0.6520	0.0122	0.0076	0.0252
O25	8.2696	0.0534	0.5780	0.0140	4.2370	2.0832	0.0548	0.2692	0.0098	0.1102	25.2170	0.0126	0.7010	0.0130	0.0062	0.0248
P1	8.3362	0.0496	0.5858	0.0152	4.2816	2.1272	0.0584	0.2378	0.0098	0.1086	24.3024	0.0126	0.6972	0.0126	0.0066	0.0250
P2	6.8276	0.0424	0.5930	0.0134	4.1602	1.9296	0.0152	0.2746	0.0094	0.1280	22.6444	0.0122	0.6754	0.0142	0.0046	0.0258
P3	6.7582	0.0422	0.6284	0.0108	4.2952	1.9128	0.0216	0.2636	0.0094	0.1192	22.7024	0.0114	0.6756	0.0126	0.0050	0.0260
P4	6.3782	0.0428	0.5910	0.0120	4.6174	1.8214	0.0162	0.3342	0.0086	0.1350	20.4000	0.0118	0.6382	0.0116	0.0046	0.0240
P5	5.0956	0.0314	0.6904	0.0096	2.3756	1.5580	0.0162	0.3246	0.0066	0.1956	19.2356	0.0118	0.5044	0.0082	0.0062	0.0212
P6	7.1222	0.0504	0.5692	0.0134	5.1860	2.0422	0.0270	0.2536	0.0080	0.0834	21.7086	0.0126	0.6912	0.0140	0.0062	0.0270
P7	6.8442	0.0522	0.5512	0.0160	5.1356	1.9248	0.0384	0.2408	0.0084	0.0970	21.9124	0.0130	0.6548	0.0130	0.0060	0.0234
P8	6.1184	0.0446	0.4932	0.0146	4.0756	1.9274	0.0158	0.2680	0.0080	0.1364	19.9530	0.0116	0.6708	0.0138	0.0040	0.0232
P9	6.8894	0.0446	0.6164	0.0126	3.8664	1.8608	0.0502	0.3056	0.0088	0.1052	22.7246	0.0124	0.6496	0.0116	0.0070	0.0254
P10	6.9538	0.0460	0.6338	0.0126	3.7470	1.9752	0.0764	0.3314	0.0092	0.1206	22.4200	0.0122	0.6526	0.0122	0.0072	0.0246
P11	7.1934	0.0462	0.5872	0.0132	3.6938	1.9188	0.0584	0.3242	0.0084	0.0960	24.5664	0.0126	0.6550	0.0118	0.0068	0.0242
P12	7.7574	0.0448	0.5516	0.0114	4.3796	1.8722	0.0506	0.2430	0.0078	0.0816	23.1482	0.0128	0.7210	0.0142	0.0096	0.0284
P13	7.5620	0.0494	0.5734	0.0138	4.5038	1.8982	0.0350	0.3004	0.0086	0.1044	23.3738	0.0134	0.6914	0.0138	0.0064	0.0278
P14	7.8316	0.0474	0.6008	0.0136	4.4558	1.9518	0.0368	0.3312	0.0078	0.0898	23.8266	0.0134	0.6818	0.0140	0.0058	0.0260
P15	7.3992	0.0410	0.5574	0.0128	4.7928	1.9112	0.0360	0.3322	0.0084	0.0912	22.0374	0.0122	0.6902	0.0142	0.0062	0.0250
P16	7.5412	0.0466	0.5594	0.0136	4.5220	1.9530	0.0460	0.3094	0.0088	0.0996	23.6574	0.0130	0.7026	0.0128	0.0058	0.0250
P17	8.6246	0.0548	0.5574	0.0134	4.3036	2.0836	0.0638	0.3180	0.0092	0.0776	24.6036	0.0140	0.7080	0.0128	0.0072	0.0256
P18	8.6046	0.0568	0.6022	0.0152	4.3854	2.0368	0.0792	0.2572	0.0088	0.0942	25.3730	0.0146	0.7092	0.0134	0.0076	0.0248
P19	7.9966	0.0504	0.6234	0.0134	4.0758	1.9200	0.0732	0.2544	0.0094	0.1104	25.5018	0.0160	0.6780	0.0130	0.0086	0.0248
P20	7.9984	0.0508	0.5792	0.0142	4.2048	1.9354	0.1188	0.2510	0.0094	0.1092	25.0032	0.0126	0.6690	0.0126	0.0084	0.0272
P21	8.6142	0.0492	0.6120	0.0128	4.3688	2.0216	0.0624	0.2278	0.0094	0.0844	25.6306	0.0134	0.7132	0.0124	0.0068	0.0284
P22	8.2810	0.0486	0.5818	0.0114	4.3972	1.9398	0.1706	0.2264	0.0092	0.0910	25.0728	0.0128	0.6990	0.0136	0.0088	0.0268
P23	8.1528	0.0528	0.5706	0.0126	4.3050	1.9442	0.1088	0.2344	0.0088	0.0964	25.9542	0.0128	0.7066	0.0128	0.0074	0.0260
P24	8.4166	0.0518	0.6064	0.0120	4.4582	2.0352	0.1188	0.2492	0.0092	0.1012	25.0192	0.0132	0.7382	0.0146	0.0068	0.0270
P25	7.6480	0.0518	0.5784	0.0134	4.2348	1.9644	0.1436	0.3224	0.0094	0.1074	24.6874	0.0126	0.6796	0.0112	0.0078	0.0252

Statistics	**Al**	**Ba**	**Ca**	**Cr**	**Fe**	**K**	**Mn**	**P**	**Rb**	**S**	**Si**	**Sr**	**Ti**	**V**	**Zn**	**Zr**
Mean	7.6537	0.0514	0.5749	0.0136	4.6072	1.9637	0.1104	0.3027	0.0091	0.1019	22.5889	0.0128	0.6662	0.0132	0.0088	0.0253
Median	7.6788	0.0506	0.5715	0.0134	4.5912	1.9408	0.0894	0.2918	0.0090	0.1012	22.6830	0.0128	0.6640	0.0132	0.0078	0.0252
SE	0.0684	0.0005	0.0042	0.0001	0.0298	0.0108	0.0063	0.0045	0.0001	0.0016	0.1182	0.0001	0.0025	0.0001	0.0003	0.0001
SD	0.9180	0.0072	0.0559	0.0015	0.3998	0.1453	0.0841	0.0608	0.0010	0.0211	1.5860	0.0009	0.0342	0.0012	0.0038	0.0017
Max	10.3592	0.0740	0.9854	0.0182	5.9380	2.4864	0.4134	0.5402	0.0124	0.1956	25.9542	0.0160	0.7530	0.0160	0.0222	0.0322
Min	5.0956	0.0314	0.4548	0.0096	2.3756	1.5580	0.0130	0.1784	0.0066	0.0428	17.5214	0.0104	0.5044	0.0082	0.0032	0.0210

Sheet 3: Correlations

		pH	EC	LOI	Magsus	Al	Ba	Ca	Cr	Fe	K	Mn	P	Rb	S	Si	Sr	Ti	V	Zn	Zr
pH	Pearson Correlation	1	-.562**	-0.137	-.324**	0.029	.177*	0.072	0.126	.193**	.240**	-.150*	-0.009	0.017	-.198**	-.160*	0.091	0.001	0.114	-0.061	-.163*
	Sig. (2-tailed)		0.000	0.067	0.000	0.698	0.018	0.336	0.094	0.010	0.001	0.046	0.902	0.826	0.008	0.033	0.227	0.986	0.128	0.419	0.029
EC	Pearson Correlation	-.562**	1	.379**	0.136	-.274**	-.306**	0.026	-.234**	-.440**	-.328**	0.047	0.033	0.059	.486**	0.009	-.256**	-.318**	-.278**	-0.066	-0.054
	Sig. (2-tailed)	0.000		0.000	0.071	0.000	0.000	0.728	0.002	0.000	0.000	0.532	0.661	0.435	0.000	0.907	0.001	0.000	0.000	0.380	0.477
LOI	Pearson Correlation	-0.137	.379**	1	-.222**	-.901**	-.811**	-.503**	-0.114	-.167*	-.766**	-.411**	0.001	-.391**	.881**	-.687**	-.771**	-.582**	-.383**	-.625**	-.506**
	Sig. (2-tailed)	0.067	0.000		0.003	0.000	0.000	0.000	0.129	0.026	0.000	0.000	0.990	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
MagSus	Pearson Correlation	-.324**	0.136	-.222**	1	.326**	.212**	.230**	-0.068	-.286**	-.185*	.709**	0.041	-0.013	-0.077	.462**	.170*	0.082	-0.017	.636**	.274**
	Sig. (2-tailed)	0.000	0.071	0.003		0.000	0.004	0.002	0.365	0.000	0.013	0.000	0.582	0.859	0.306	0.000	0.023	0.274	0.822	0.000	0.000
Al	Pearson Correlation	0.029	-.274**	-.901**	.326**	1	.824**	.529**	.156*	.177*	.770**	.480**	0.081	.418**	-.776**	.744**	.743**	.594**	.357**	.682**	.556**
	Sig. (2-tailed)	0.698	0.000	0.000	0.000		0.000	0.000	0.038	0.018	0.000	0.000	0.278	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ba	Pearson Correlation	.177*	-.306**	-.811**	.212**	.824**	1	.474**	.266**	.269**	.700**	.490**	.188*	.404**	-.691**	.505**	.700**	.413**	.318**	.685**	.448**
	Sig. (2-tailed)	0.018	0.000	0.000	0.004	0.000		0.000	0.000	0.000	0.000	0.000	0.012	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	Pearson Correlation	0.072	0.026	-.503**	.230**	.529**	.474**	1	-0.095	-0.126	.338**	.268**	.180*	0.055	-.456**	.531**	.463**	.150*	0.123	.468**	.256**
	Sig. (2-tailed)	0.336	0.728	0.000	0.002	0.000	0.000		0.207	0.093	0.000	0.000	0.016	0.461	0.000	0.000	0.000	0.045	0.101	0.000	0.001
Cr	Pearson Correlation	0.126	-.234**	-0.114	-0.068	.156*	.266**	-0.095	1	.461**	.233**	0.027	.157*	.147*	-0.078	-0.132	.147*	0.091	.207**	0.063	-0.057
	Sig. (2-tailed)	0.094	0.002	0.129	0.365	0.038	0.000	0.207		0.000	0.002	0.724	0.036	0.049	0.298	0.077	0.049	0.227	0.006	0.402	0.451
Fe	Pearson Correlation	.193**	-.440**	-.167*	-.286**	.177*	.269**	-0.126	.461**	1	.263**	-0.055	.188*	0.053	-0.146	-.379**	0.138	.148*	.344**	0.046	0.003
	Sig. (2-tailed)	0.010	0.000	0.026	0.000	0.018	0.000	0.093	0.000		0.000	0.468	0.012	0.481	0.051	0.000	0.065	0.049	0.000	0.537	0.970
K	Pearson Correlation	.240**	-.328**	-.766**	-.185*	.770**	.700**	.338**	.233**	.263**	1	0.062	0.006	.574**	-.731**	.464**	.632**	.640**	.352**	.277**	.497**
	Sig. (2-tailed)	0.001	0.000	0.000	0.013	0.000	0.000	0.000	0.002	0.000		0.412	0.935	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mn	Pearson Correlation	-.150*	0.047	-.411**	.709**	.480**	.490**	.268**	0.027	-0.055	0.062	1	.230**	.230**	-.183*	.363**	.256**	0.071	0.094	.827**	.275**
	Sig. (2-tailed)	0.046	0.532	0.000	0.000	0.000	0.000	0.000	0.724	0.468	0.412		0.002	0.002	0.014	0.000	0.001	0.346	0.211	0.000	0.000
P	Pearson Correlation	-0.009	0.033	0.001	0.041	0.081	.188*	.180*	.157*	.188*	0.006	.230**	1	0.141	0.058	-.162*	0.056	-0.127	0.011	.200**	-0.016
	Sig. (2-tailed)	0.902	0.661	0.990	0.582	0.278	0.012	0.016	0.036	0.012	0.935	0.002		0.060	0.441	0.030	0.456	0.091	0.883	0.007	0.833
Rb	Pearson Correlation	0.017	0.059	-.391**	-0.013	.418**	.404**	0.055	.147*	0.053	.574**	.230**	0.141	1	-.247**	.277**	.350**	.449**	.239**	.196**	.448**
	Sig. (2-tailed)	0.826	0.435	0.000	0.859	0.000	0.000	0.461	0.049	0.481	0.000	0.002	0.060		0.001	0.000	0.000	0.000	0.001	0.009	0.000
S	Pearson Correlation	-.198**	.486**	.881**	-0.077	-.776**	-.691**	-.456**	-0.078	-0.146	-.731**	-.183*	0.058	-.247**	1	-.605**	-.648**	-.526**	-.311**	-.417**	-.484**
	Sig. (2-tailed)	0.008	0.000	0.000	0.306	0.000	0.000	0.000	0.298	0.051	0.000	0.014	0.441	0.001		0.000	0.000	0.000	0.000	0.000	0.000
Si	Pearson Correlation	-.160*	0.009	-.687**	.462**	.744**	.505**	.531**	-0.132	-.379**	.464**	.363**	-.162*	.277**	-.605**	1	.584**	.459**	0.108	.463**	.479**
	Sig. (2-tailed)	0.033	0.907	0.000	0.000	0.000	0.000	0.000	0.077	0.000	0.000	0.000	0.030	0.000	0.000		0.000	0.000	0.149	0.000	0.000
Sr	Pearson Correlation	0.091	-.256**	-.771**	.170*	.743**	.700**	.463**	.147*	0.138	.632**	.256**	0.056	.350**	-.648**	.584**	1	.508**	.337**	.505**	.416**

	Sig. (2-tailed)	0.227	0.001	0.000	0.023	0.000	0.000	0.000	0.049	0.065	0.000	0.001	0.456	0.000	0.000	0.000		0.000	0.000	0.000	0.000
Ti	Pearson Correlation	0.001	-.318**	-.582**	0.082	.594**	.413**	.150*	0.091	.148*	.640**	0.071	-0.127	.449**	-.526**	.459**	.508**	1	.424**	.192*	.578**
	Sig. (2-tailed)	0.986	0.000	0.000	0.274	0.000	0.000	0.045	0.227	0.049	0.000	0.346	0.091	0.000	0.000	0.000	0.000		0.000	0.010	0.000
V	Pearson Correlation	0.114	-.278**	-.383**	-0.017	.357**	.318**	0.123	.207**	.344**	.352**	0.094	0.011	.239**	-.311**	0.108	.337**	.424**	1	.250**	.262**
	Sig. (2-tailed)	0.128	0.000	0.000	0.822	0.000	0.000	0.101	0.006	0.000	0.000	0.211	0.883	0.001	0.000	0.149	0.000	0.000		0.001	0.000
Zn	Pearson Correlation	-0.061	-0.066	-.625**	.636**	.682**	.685**	.468**	0.063	0.046	.277**	.827**	.200**	.196**	-.417**	.463**	.505**	.192*	.250**	1	.376**
	Sig. (2-tailed)	0.419	0.380	0.000	0.000	0.000	0.000	0.000	0.402	0.537	0.000	0.000	0.007	0.009	0.000	0.000	0.000	0.010	0.001		0.000
Zr	Pearson Correlation	-.163*	-0.054	-.506**	.274**	.556**	.448**	.256**	-0.057	0.003	.497**	.275**	-0.016	.448**	-.484**	.479**	.416**	.578**	.262**	.376**	1
	Sig. (2-tailed)	0.029	0.477	0.000	0.000	0.000	0.000	0.001	0.451	0.970	0.000	0.000	0.833	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Sheet 4: Grid coordinates and PCA results (excluding grid square P5)

Grid	POINT X	POINT Y	PC1	PC2	PC3	PC4	PC5
A1	313912.2677	763767.0716	-2.85	-1.90	-0.27	-1.92	-0.04
A2	313912.7572	763767.2436	-1.85	-0.69	-1.56	-2.24	0.73
A3	313913.207	763767.4156	-2.43	-2.68	0.44	-1.18	-0.60
A4	313913.7097	763767.5875	2.84	-2.35	-1.01	1.78	-0.09
A5	313914.1595	763767.7463	3.11	-1.47	-1.39	1.39	0.47
A6	313914.6357	763767.9315	-0.42	-0.07	-0.81	0.21	1.17
A7	313915.0855	763768.0902	2.89	-1.72	-1.02	2.20	0.87
A8	313915.5485	763768.2755	4.10	-3.37	-0.89	2.06	0.10
A9	313916.0116	763768.4342	1.02	-2.28	0.37	1.84	0.80
A10	313916.4746	763768.6062	-6.21	-1.34	3.23	2.22	1.46
A11	313916.9773	763768.7782	-5.32	-0.38	0.12	1.15	-0.32
A12	313917.4271	763768.9501	-2.25	0.13	-0.22	1.40	-0.08
A13	313917.8372	763769.0957	-2.35	-3.33	0.88	-1.35	-0.56
B1	313912.0799	763767.5584	-3.26	-2.56	0.05	-1.08	-0.53
B2	313912.5773	763767.7278	-0.72	-3.28	-0.26	-2.08	-0.95
B3	313913.0324	763767.8865	1.43	-2.66	-1.40	-2.00	-0.62
B4	313913.5192	763768.077	-1.27	-1.79	-0.50	-0.02	-0.68
B5	313913.9954	763768.2464	3.35	-1.89	-0.53	1.40	0.36
B6	313914.4505	763768.4157	4.02	-1.53	-1.27	1.23	1.37
B7	313914.9162	763768.585	2.80	-2.96	0.31	2.11	0.12
B8	313915.3607	763768.7544	3.63	-3.03	1.11	1.50	0.30
B9	313915.8369	763768.9237	2.42	-1.53	0.59	1.09	0.82
B11	313916.7894	763769.2835	5.14	-3.74	3.36	2.89	0.82
B12	313917.2551	763769.4423	0.53	-0.36	1.02	2.69	1.39
B13	313917.6679	763769.5904	-0.55	-2.36	0.89	-1.28	0.71
C1	313911.9066	763768.0545	-4.55	-1.77	-0.17	-3.53	-0.33
C2	313912.404	763768.2239	-1.41	-2.97	0.07	-1.00	-1.69
C3	313912.8485	763768.3932	0.59	-1.73	-0.75	-0.20	-0.34
C7	313914.7217	763769.0811	4.48	-2.29	-0.17	1.69	0.30
C8	313915.1874	763769.2504	3.92	-0.83	-0.36	0.03	0.89
C11	313916.6161	763769.769	-0.63	-0.44	1.58	0.60	0.94
C12	313917.0818	763769.9384	0.32	-0.59	-0.15	0.50	0.42
C13	313917.4946	763770.0865	-2.73	-1.82	-0.38	-0.51	-0.79
D1	313911.7372	763768.5308	-1.89	-2.65	-0.21	-1.77	-1.64
D2	313912.2241	763768.7001	-4.08	-0.61	-0.66	-1.54	-0.11

D3	313912.6686	763768.8694	-1.22	-0.93	-1.13	-1.47	0.20
D4	313913.166	763769.0494	-1.90	-1.42	-1.14	0.08	-1.07
D8	313915.0181	763769.7161	6.20	-0.79	0.73	-1.89	0.26
D9	313915.4837	763769.8854	4.36	0.00	-0.45	-1.24	1.81
D10	313915.9494	763770.0654	1.82	-2.78	3.41	0.45	1.33
D11	313916.4362	763770.2453	0.92	-0.94	1.39	0.14	0.23
D12	313916.9019	763770.4146	-0.07	-1.33	-1.61	-0.22	-1.25
D13	313917.3464	763770.5734	-2.71	-0.14	-2.45	-0.37	0.12
E1	313911.5573	763768.9753	-1.41	-0.58	-0.79	-0.62	1.10
E2	313912.0547	763769.1552	-0.67	-1.33	-0.43	-2.94	1.29
E3	313912.5098	763769.3245	1.36	-0.68	-0.82	-0.65	0.53
E4	313913.0072	763769.4939	2.90	-2.23	-0.34	0.56	0.57
E5	313913.4729	763769.6738	-1.15	0.40	-1.64	0.98	1.19
E8	313914.8487	763770.1924	7.49	-2.60	-1.39	0.51	0.47
E9	313915.3144	763770.3511	6.03	-2.03	-1.31	0.86	0.26
E10	313915.7906	763770.5099	3.95	-2.75	1.46	1.54	0.51
E11	313916.2669	763770.7109	-3.09	-0.03	1.86	-0.19	-0.10
E12	313916.7431	763770.8697	1.81	-0.52	-3.15	0.53	-0.54
E13	313917.1771	763771.0284	-0.38	-1.37	-1.39	-0.23	-0.75
F1	313911.388	763769.4674	-0.83	-2.19	-1.02	-0.93	-0.83
F2	313911.8854	763769.6473	0.90	-2.31	-0.87	-0.85	-1.29
F3	313912.3299	763769.8167	-1.02	-1.10	0.26	-0.92	-0.12
F4	313912.8167	763769.986	-0.53	0.63	-0.09	1.28	1.91
F5	313913.2824	763770.1553	-0.37	-0.24	0.60	0.93	1.68
F8	313914.6688	763770.6633	6.76	-2.44	0.06	-2.70	1.74
F9	313915.1451	763770.8432	5.63	-2.50	0.81	-2.38	2.98
F11	313916.0976	763771.2031	3.06	-1.52	0.72	0.20	1.65
F12	313916.5526	763771.3618	-2.16	-1.05	2.16	2.18	0.77
F13	313916.9971	763771.5206	-2.97	-1.60	1.64	-0.12	-0.10
G4	313912.6514	763770.4741	-3.52	1.65	-0.14	-1.63	2.34
G5	313913.117	763770.6435	-3.76	1.75	-0.03	0.50	1.98
G6	313913.5721	763770.8128	-1.22	0.82	-0.02	-1.58	1.68
H4	313912.4714	763770.9504	-5.60	-0.10	1.43	-2.10	1.47
H5	313912.9477	763771.1303	-5.65	0.75	0.80	0.30	0.66
H6	313913.4028	763771.2996	-3.52	0.17	-0.73	-0.42	-0.27
K11	313915.1914	763773.6756	1.21	1.06	0.50	-0.28	0.67
K12	313915.657	763773.8344	0.53	1.91	-0.25	0.66	0.13
K13	313916.1439	763774.0143	-1.16	1.69	-0.08	0.24	0.41
K14	313916.6201	763774.1836	1.32	1.62	1.12	1.26	-0.73

K15	313917.1069	763774.3635	0.01	1.06	-0.59	-0.04	-0.63
K16	313917.6202	763774.554	-0.27	1.65	-0.42	0.03	-0.01
K17	313918.1071	763774.7234	1.09	1.55	0.30	0.75	0.63
K18	313918.5833	763774.9033	-0.01	1.39	0.31	-0.33	-0.34
K19	313919.0596	763775.0726	0.79	0.97	0.24	-0.63	-0.80
K20	313919.6099	763775.2843	1.87	0.64	0.61	-0.15	-1.21
K21	313920.0756	763775.4536	4.09	0.20	0.16	-2.01	-0.70
K22	313920.5942	763775.6441	5.07	-0.03	-1.44	-1.65	-0.35
K23	313921.0598	763775.8029	4.73	0.16	-1.66	-0.21	-0.24
L11	313915.0167	763774.1624	-0.52	1.87	-0.14	-0.22	1.08
L12	313915.4824	763774.3318	0.82	1.56	-1.09	0.59	0.29
L13	313915.9798	763774.5011	-0.79	2.06	-0.92	0.41	0.75
L14	313916.4561	763774.681	2.00	1.02	-0.37	0.15	-0.64
L15	313916.9323	763774.8609	2.41	0.55	-0.36	-0.28	-2.13
L16	313917.4403	763775.0409	1.11	0.48	-0.40	0.03	-0.81
L17	313917.9272	763775.2208	1.82	0.41	0.19	0.41	-0.37
L18	313918.4193	763775.3954	2.57	0.96	0.48	-1.37	-0.31
L19	313918.885	763775.5753	1.37	1.99	0.95	-0.35	-0.62
L20	313919.4141	763775.7658	1.45	1.85	1.34	-0.29	-1.56
L21	313919.9115	763775.9352	3.30	1.85	1.25	-0.67	-1.64
L22	313920.409	763776.1362	3.76	2.03	2.36	-2.17	1.08
M12	313915.3078	763774.8027	-0.04	0.97	-0.24	-0.26	0.17
M13	313915.7946	763774.9721	0.14	1.74	-0.56	0.29	-0.90
M14	313916.2709	763775.1626	1.51	1.03	-0.89	0.17	-0.43
M15	313916.7471	763775.3425	1.23	1.28	0.60	-0.45	-1.11
M19	313918.705	763776.041	1.31	0.41	0.92	-1.06	-0.91
M20	313919.2607	763776.2474	2.59	2.16	1.45	-0.89	-1.17
M21	313919.7157	763776.4167	2.28	2.12	2.32	-1.09	-1.23
M22	313920.2343	763776.5966	3.80	2.37	1.84	-0.79	-0.97
M23	313920.7106	763776.766	2.25	2.02	0.83	-0.18	-0.46
M24	313921.1868	763776.9565	-0.98	2.19	1.01	1.85	-0.73
M25	313921.6419	763777.1152	-2.58	1.25	0.53	1.94	-0.28
M26	313922.1182	763777.2951	-0.05	0.51	0.58	2.00	1.38
M27	313922.6156	763777.475	-2.16	1.11	1.10	1.84	0.97
M28	313923.0813	763777.655	-1.94	0.40	1.40	0.82	0.60
N1	313909.9473	763773.3899	-2.24	0.61	-1.87	0.92	1.10
N2	313910.4341	763773.5592	-3.57	-0.01	-1.29	0.09	0.19
N3	313910.9104	763773.7497	-2.64	-1.07	-0.39	-0.21	0.18
N4	313911.3972	763773.9084	-5.92	-1.03	2.83	0.07	1.36

N5	313911.8629	763774.0884	-6.62	-1.71	2.56	1.05	-1.27
N6	313912.318	763774.2577	-2.82	-1.44	-0.22	0.86	-1.06
N7	313912.7836	763774.427	-3.56	-3.23	1.72	0.40	-2.13
N8	313913.2493	763774.5964	-3.01	-0.59	0.17	-0.65	-0.94
N9	313913.7044	763774.7551	-2.46	0.68	0.41	-1.14	1.52
N10	313914.1806	763774.935	-3.86	0.44	0.23	-1.13	1.56
N13	313915.6306	763775.4642	-0.47	1.60	-0.37	0.96	-0.33
N14	313916.0962	763775.6335	0.94	2.12	-0.51	-0.02	-0.29
N15	313916.5725	763775.8134	0.48	2.16	0.19	-0.61	-0.76
N19	313918.5304	763776.5331	2.49	1.12	3.77	-1.15	-1.93
N20	313919.0702	763776.7236	2.11	2.06	3.20	-3.04	0.27
N21	313919.5358	763776.9035	4.04	3.74	3.34	-2.55	4.30
N22	313920.065	763777.0835	3.73	2.04	2.73	-0.11	-1.26
N23	313920.5307	763777.2528	3.44	2.35	1.45	1.57	-1.83
N24	313921.0069	763777.4327	-1.65	1.60	-0.44	0.20	-0.86
N25	313921.4726	763777.602	-1.44	1.07	1.61	0.88	-0.46
N26	313921.9488	763777.7714	-0.68	1.42	-1.20	1.14	-0.43
N27	313922.4357	763777.9619	-1.03	0.31	0.76	0.29	0.05
N28	313922.9119	763778.1418	2.83	-0.19	-0.95	0.95	0.90
O1	313909.7727	763773.8926	-2.13	1.16	-0.91	0.97	1.57
O2	313910.2595	763774.0725	-4.37	1.50	-3.47	0.09	-0.22
O3	313910.7252	763774.2418	-4.77	0.68	-0.64	1.41	-0.35
O4	313911.2014	763774.4217	-4.25	0.24	0.88	2.10	1.58
O5	313911.6777	763774.5805	-6.85	-0.96	1.19	0.81	-1.07
O6	313912.1434	763774.771	-0.89	-2.55	0.69	0.76	-0.84
O7	313912.5984	763774.9297	-1.84	-4.13	1.84	0.68	-1.66
O8	313913.0535	763775.0885	-1.17	-2.20	0.31	-1.29	-0.56
O9	313913.5192	763775.2684	-1.64	0.17	-0.96	-0.96	0.15
O10	313913.9954	763775.4272	-1.05	0.15	-0.26	-1.21	0.61
O13	313915.4348	763775.9563	-1.06	1.24	0.09	0.05	0.03
O14	313915.9322	763776.1468	-1.88	2.50	-0.50	0.41	-1.08
O15	313916.3873	763776.3056	-0.92	1.31	1.23	1.03	-0.88
O16	313916.9059	763776.5067	0.52	1.46	-0.94	-0.64	0.29
O17	313917.4033	763776.676	0.50	1.18	0.47	0.42	-0.10
O18	313917.8689	763776.8347	0.74	1.27	1.03	-0.96	-0.37
O19	313918.3769	763777.0252	-0.10	2.62	-0.38	-0.01	0.06
O20	313918.8744	763777.2157	0.78	2.52	1.74	1.42	-0.88
O21	313919.3612	763777.3957	1.12	3.12	4.50	-0.16	-1.94
O22	313919.8692	763777.565	1.86	1.58	1.06	1.93	-1.82

O23	313920.3349	763777.7555	-0.96	2.71	0.14	0.12	0.00
O24	313920.8217	763777.9248	-0.51	2.72	-1.80	0.18	0.60
O25	313921.298	763778.0942	0.49	0.54	-2.04	1.12	0.65
P1	313909.6033	763774.3794	0.44	-0.58	-1.80	0.39	0.60
P2	313910.0902	763774.5487	-2.32	0.16	-1.79	1.24	0.38
P3	313910.5453	763774.7287	-2.55	1.23	-2.51	0.68	1.10
P4	313911.0427	763774.898	-4.63	0.56	-0.23	0.43	1.50
P6	313911.974	763775.2472	-0.11	-1.82	-0.99	0.37	-0.91
P7	313912.4185	763775.3954	-1.07	-3.00	0.66	-1.37	-0.84
P8	313912.8842	763775.5647	-4.05	-2.68	-0.15	-1.21	-0.95
P9	313913.3499	763775.7552	-2.00	1.88	-1.26	-0.80	1.04
P10	313913.8155	763775.914	-1.73	1.84	-0.73	-0.88	1.52
P11	313914.3024	763776.0939	-1.12	1.74	-1.25	-1.60	0.68
P12	313914.7786	763776.2632	0.60	1.01	-1.99	-0.11	-2.83
P13	313915.276	763776.4537	0.28	1.40	-0.71	0.85	-1.46
P14	313915.7417	763776.6231	0.20	-0.27	-0.97	-0.58	-0.25
P15	313916.2285	763776.803	-0.98	-0.58	-0.25	-0.10	-1.25
P16	313916.7365	763776.9935	-0.32	0.10	-1.00	0.10	-0.45
P17	313917.2128	763777.1734	2.19	-0.48	-1.40	-0.70	0.05
P18	313917.7102	763777.3322	2.18	0.74	-1.19	0.13	-0.44
P19	313918.1759	763777.5015	1.30	2.49	-1.62	-0.03	0.25
P20	313918.7156	763777.692	0.34	2.57	-1.27	1.13	-0.44
P21	313919.1919	763777.8719	2.10	0.91	-2.88	0.05	-0.58
P22	313919.7052	763778.0624	1.43	1.72	-1.74	-0.22	-1.66
P23	313920.1708	763778.2317	1.05	1.62	-2.13	0.00	-0.95
P24	313920.6365	763778.4011	1.82	0.95	-2.41	1.09	-0.69
P25	313921.1022	763778.5598	0.00	1.72	-0.87	0.15	1.03

Sheet 5: Grid coordinates, k-means results and area membership

Grid	POINT X	POINT Y	Area	k-means cluster
A1	313912.2677	763767.0716	Exterior	2
A2	313912.7572	763767.2436	Turf wall	2
A3	313913.207	763767.4156	Turf wall	2
A4	313913.7097	763767.5875	Turf wall	4
A5	313914.1595	763767.7463	Turf wall	4
A6	313914.6357	763767.9315	Turf wall	1
A7	313915.0855	763768.0902	Turf wall	4
A8	313915.5485	763768.2755	Turf wall	4
A9	313916.0116	763768.4342	Turf wall	4
A10	313916.4746	763768.6062	Turf wall	2
A11	313916.9773	763768.7782	Turf wall	2
A12	313917.4271	763768.9501	Turf wall	2
A13	313917.8372	763769.0957	Turf wall	2
B1	313912.0799	763767.5584	Turf wall	2
B2	313912.5773	763767.7278	Turf wall	2
B3	313913.0324	763767.8865	Turf wall	4
B4	313913.5192	763768.077	Turf wall	2
B5	313913.9954	763768.2464	Turf wall	4
B6	313914.4505	763768.4157	Annexe	4
B7	313914.9162	763768.585	Annexe	4
B8	313915.3607	763768.7544	Annexe	4
B9	313915.8369	763768.9237	Annexe	4
B11	313916.7894	763769.2835	Annexe	4
B12	313917.2551	763769.4423	Turf wall	1
B13	313917.6679	763769.5904	Turf wall	2
C1	313911.9066	763768.0545	Turf wall	2
C2	313912.404	763768.2239	Turf wall	2
C3	313912.8485	763768.3932	Turf wall	1
C7	313914.7217	763769.0811	Annexe	4
C8	313915.1874	763769.2504	Annexe	4
C11	313916.6161	763769.769	Annexe	1
C12	313917.0818	763769.9384	Annexe	1
C13	313917.4946	763770.0865	Annexe	2
D1	313911.7372	763768.5308	Turf wall	2
D2	313912.2241	763768.7001	Turf wall	2

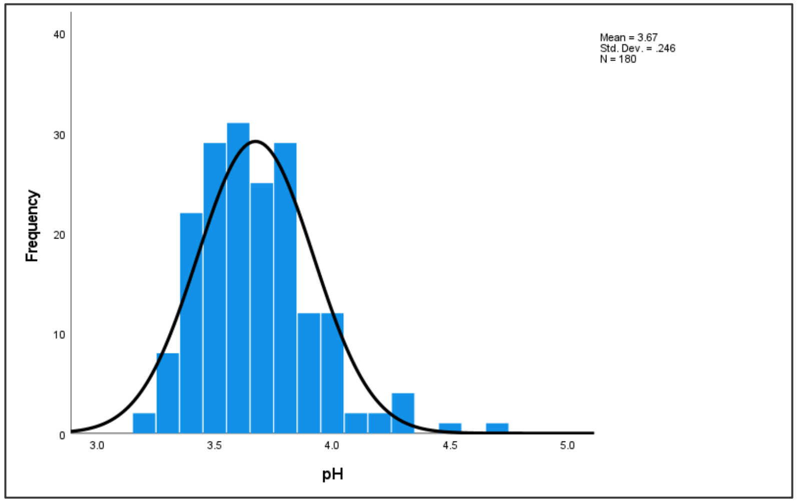
D3	313912.6686	763768.8694	Annexe	2
D4	313913.166	763769.0494	Annexe	2
D8	313915.0181	763769.7161	Annexe	4
D9	313915.4837	763769.8854	Annexe	4
D10	313915.9494	763770.0654	Annexe	4
D11	313916.4362	763770.2453	Annexe	1
D12	313916.9019	763770.4146	Annexe	1
D13	313917.3464	763770.5734	Annexe	2
E1	313911.5573	763768.9753	Turf wall	2
E2	313912.0547	763769.1552	Turf wall	2
E3	313912.5098	763769.3245	Annexe	1
E4	313913.0072	763769.4939	Annexe	4
E5	313913.4729	763769.6738	Annexe	1
E8	313914.8487	763770.1924	Annexe	4
E9	313915.3144	763770.3511	Annexe	4
E10	313915.7906	763770.5099	Annexe	4
E11	313916.2669	763770.7109	Annexe	2
E12	313916.7431	763770.8697	Annexe	1
E13	313917.1771	763771.0284	Annexe	1
F1	313911.388	763769.4674	Turf wall	2
F2	313911.8854	763769.6473	Turf wall	1
F3	313912.3299	763769.8167	Annexe	2
F4	313912.8167	763769.986	Annexe	1
F5	313913.2824	763770.1553	Annexe	1
F8	313914.6688	763770.6633	Annexe	4
F9	313915.1451	763770.8432	Annexe	4
F11	313916.0976	763771.2031	Annexe	4
F12	313916.5526	763771.3618	Annexe	2
F13	313916.9971	763771.5206	Annexe	2
G4	313912.6514	763770.4741	Annexe	2
G5	313913.117	763770.6435	Annexe	2
G6	313913.5721	763770.8128	Annexe	1
H4	313912.4714	763770.9504	Annexe	2
H5	313912.9477	763771.1303	Annexe	2
H6	313913.4028	763771.2996	Annexe	2
K11	313915.1914	763773.6756	Living	1
K12	313915.657	763773.8344	Living	1
K13	313916.1439	763774.0143	Living	1
K14	313916.6201	763774.1836	Living	3

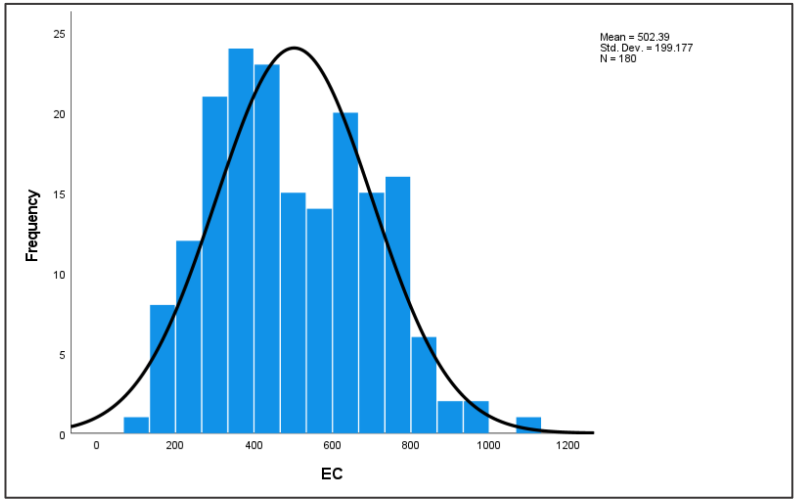
K15	313917.1069	763774.3635	Living	1
K16	313917.6202	763774.554	Living	1
K17	313918.1071	763774.7234	Living	1
K18	313918.5833	763774.9033	Living	1
K19	313919.0596	763775.0726	Living	1
K20	313919.6099	763775.2843	Living	3
K21	313920.0756	763775.4536	Byre	3
K22	313920.5942	763775.6441	Byre	4
K23	313921.0598	763775.8029	Byre	4
L11	313915.0167	763774.1624	Living	1
L12	313915.4824	763774.3318	Living	1
L13	313915.9798	763774.5011	Living	1
L14	313916.4561	763774.681	Living	1
L15	313916.9323	763774.8609	Living	3
L16	313917.4403	763775.0409	Living	1
L17	313917.9272	763775.2208	Living	1
L18	313918.4193	763775.3954	Living	3
L19	313918.885	763775.5753	Living	3
L20	313919.4141	763775.7658	Living	3
L21	313919.9115	763775.9352	Byre	3
L22	313920.409	763776.1362	Byre	3
M12	313915.3078	763774.8027	Living	1
M13	313915.7946	763774.9721	Living	1
M14	313916.2709	763775.1626	Living	1
M15	313916.7471	763775.3425	Living	3
M19	313918.705	763776.041	Living	3
M20	313919.2607	763776.2474	Living	3
M21	313919.7157	763776.4167	Byre	3
M22	313920.2343	763776.5966	Byre	3
M23	313920.7106	763776.766	Byre	3
M24	313921.1868	763776.9565	Byre	1
M25	313921.6419	763777.1152	Byre	2
M26	313922.1182	763777.2951	Byre	1
M27	313922.6156	763777.475	Byre	1
M28	313923.0813	763777.655	Byre	2
N1	313909.9473	763773.3899	Exterior	1
N2	313910.4341	763773.5592	Exterior	2
N3	313910.9104	763773.7497	Exterior	2
N4	313911.3972	763773.9084	Turf wall	2

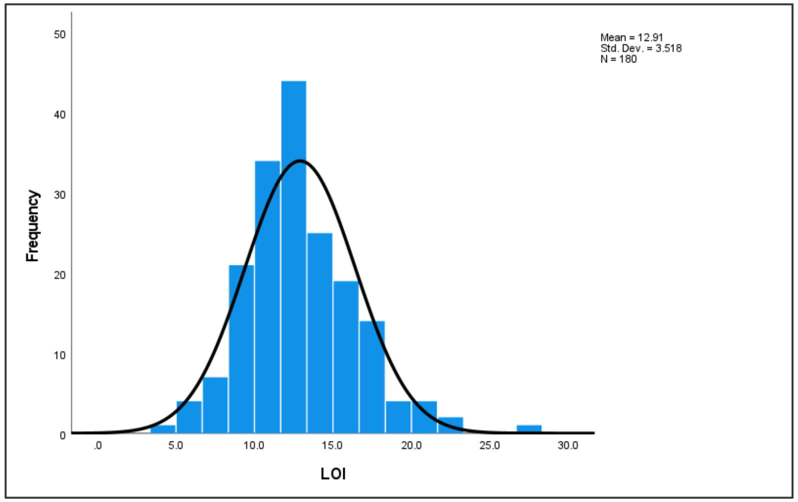
N5	313911.8629	763774.0884	Turf wall	2
N6	313912.318	763774.2577	Turf wall	2
N7	313912.7836	763774.427	Turf wall	2
N8	313913.2493	763774.5964	Living	2
N9	313913.7044	763774.7551	Living	2
N10	313914.1806	763774.935	Living	2
N13	313915.6306	763775.4642	Living	1
N14	313916.0962	763775.6335	Living	1
N15	313916.5725	763775.8134	Living	1
N19	313918.5304	763776.5331	Living	3
N20	313919.0702	763776.7236	Living	3
N21	313919.5358	763776.9035	Byre	3
N22	313920.065	763777.0835	Byre	3
N23	313920.5307	763777.2528	Byre	3
N24	313921.0069	763777.4327	Byre	1
N25	313921.4726	763777.602	Byre	1
N26	313921.9488	763777.7714	Byre	1
N27	313922.4357	763777.9619	Byre	1
N28	313922.9119	763778.1418	Byre	4
O1	313909.7727	763773.8926	Exterior	1
O2	313910.2595	763774.0725	Exterior	2
O3	313910.7252	763774.2418	Exterior	2
O4	313911.2014	763774.4217	Turf wall	2
O5	313911.6777	763774.5805	Turf wall	2
O6	313912.1434	763774.771	Turf wall	2
O7	313912.5984	763774.9297	Turf wall	2
O8	313913.0535	763775.0885	Living	2
O9	313913.5192	763775.2684	Living	1
O10	313913.9954	763775.4272	Living	1
O13	313915.4348	763775.9563	Living	1
O14	313915.9322	763776.1468	Living	1
O15	313916.3873	763776.3056	Living	1
O16	313916.9059	763776.5067	Living	1
O17	313917.4033	763776.676	Living	1
O18	313917.8689	763776.8347	Living	1
O19	313918.3769	763777.0252	Living	1
O20	313918.8744	763777.2157	Living	3
O21	313919.3612	763777.3957	Byre	3
O22	313919.8692	763777.565	Byre	3

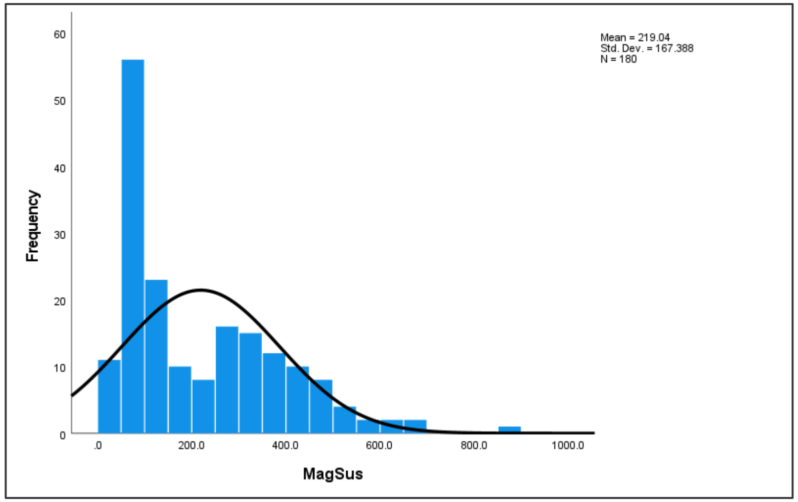
O23	313920.3349	763777.7555	Byre	1
O24	313920.8217	763777.9248	Byre	1
O25	313921.298	763778.0942	Byre	1
P1	313909.6033	763774.3794	Exterior	1
P2	313910.0902	763774.5487	Exterior	2
P3	313910.5453	763774.7287	Exterior	1
P4	313911.0427	763774.898	Turf wall	2
P5	313911.5189	763775.0779	Turf wall	n/a
P6	313911.974	763775.2472	Turf wall	1
P7	313912.4185	763775.3954	Turf wall	2
P8	313912.8842	763775.5647	Living	2
P9	313913.3499	763775.7552	Living	1
P10	313913.8155	763775.914	Living	1
P11	313914.3024	763776.0939	Living	1
P12	313914.7786	763776.2632	Living	1
P13	313915.276	763776.4537	Living	1
P14	313915.7417	763776.6231	Living	1
P15	313916.2285	763776.803	Living	1
P16	313916.7365	763776.9935	Living	1
P17	313917.2128	763777.1734	Living	1
P18	313917.7102	763777.3322	Living	1
P19	313918.1759	763777.5015	Living	1
P20	313918.7156	763777.692	Living	1
P21	313919.1919	763777.8719	Byre	1
P22	313919.7052	763778.0624	Byre	1
P23	313920.1708	763778.2317	Byre	1
P24	313920.6365	763778.4011	Byre	1
P25	313921.1022	763778.5598	Byre	1

Sheet 6: Normality of geochemical and magnetic variables

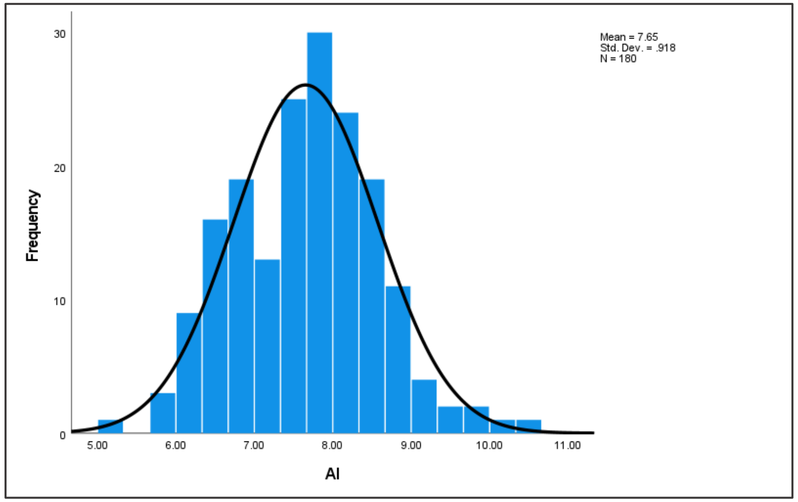


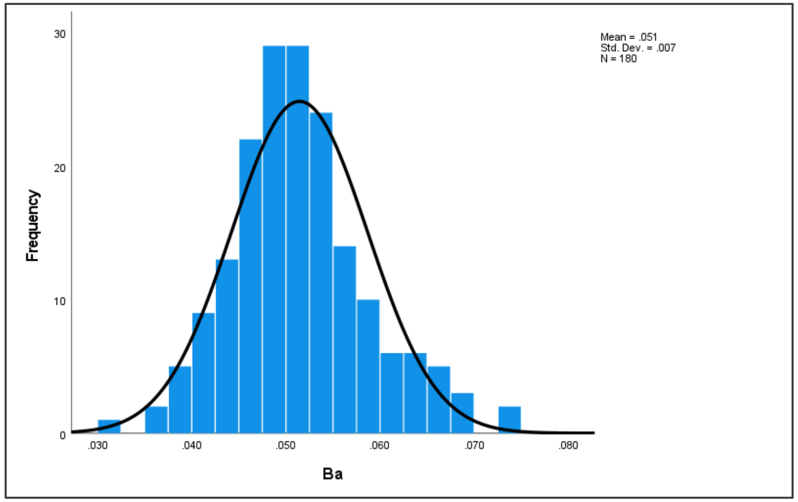


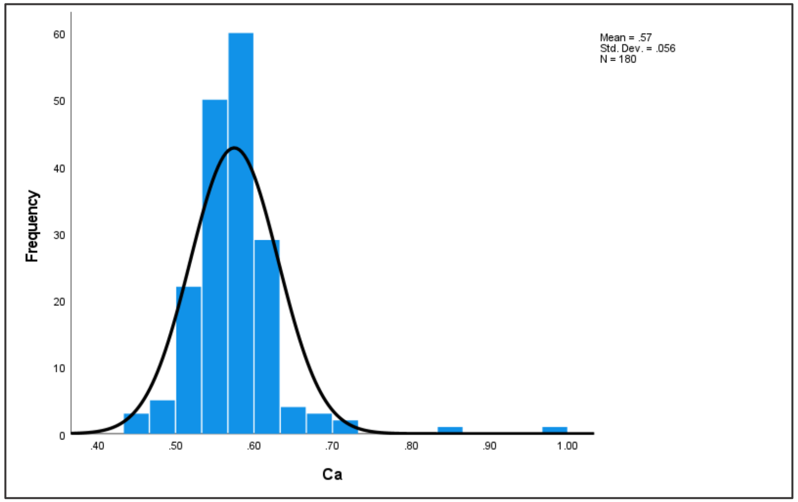


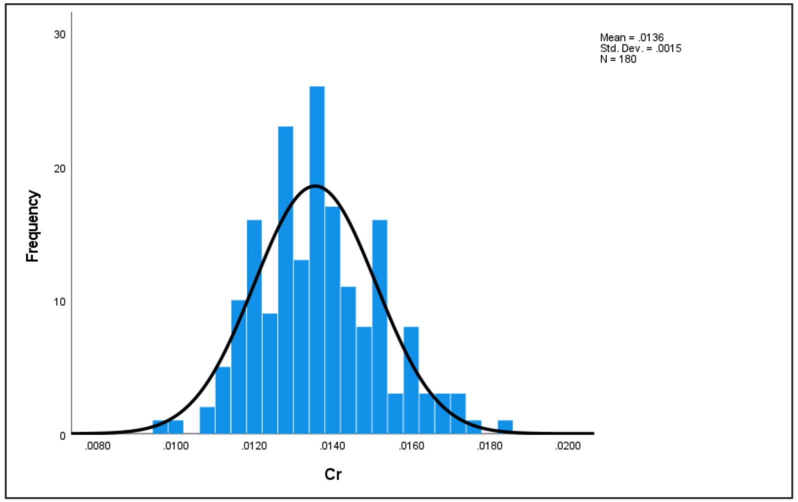


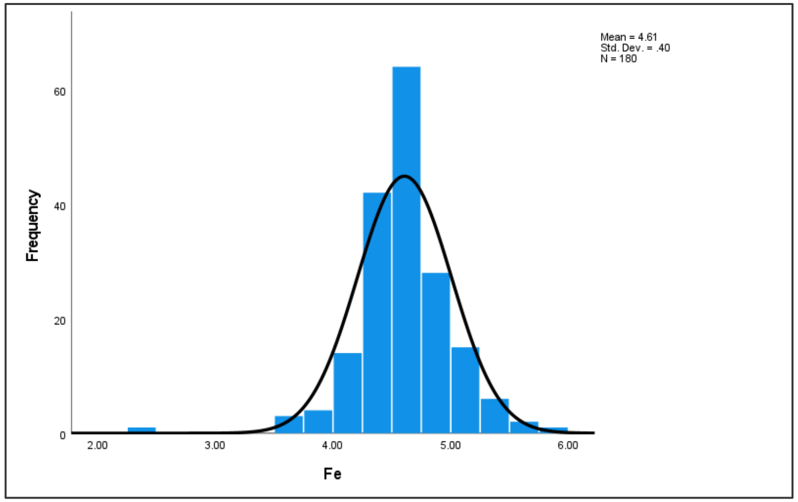
Sheet 6: Normality of multi-element variables

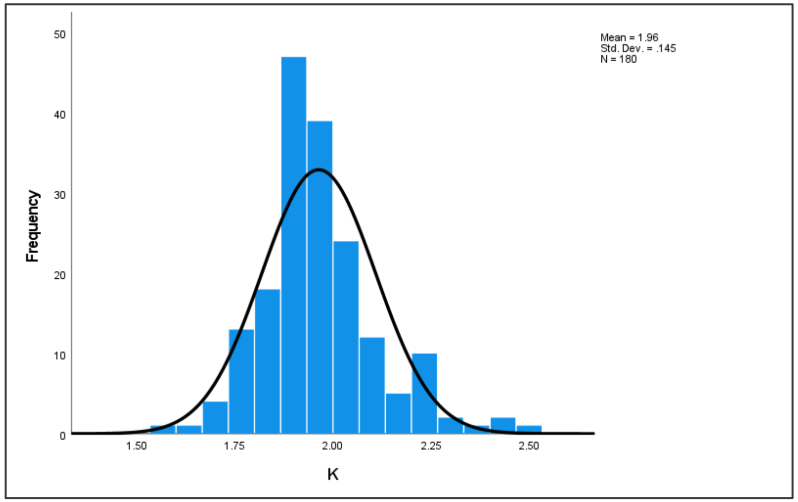


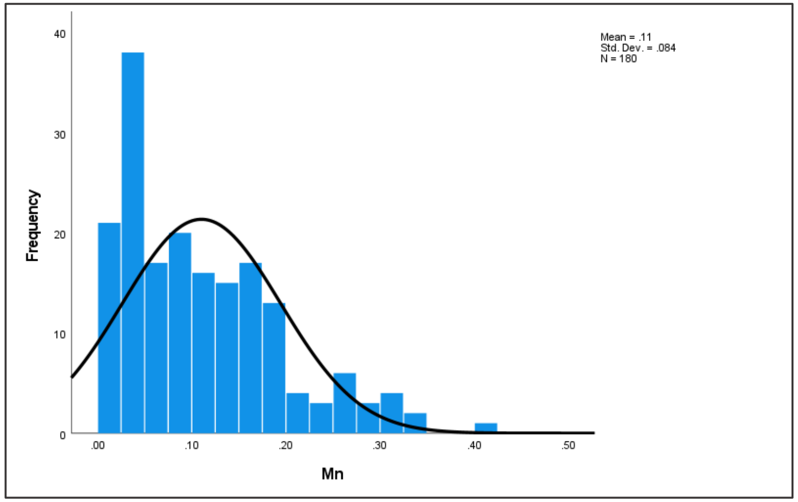


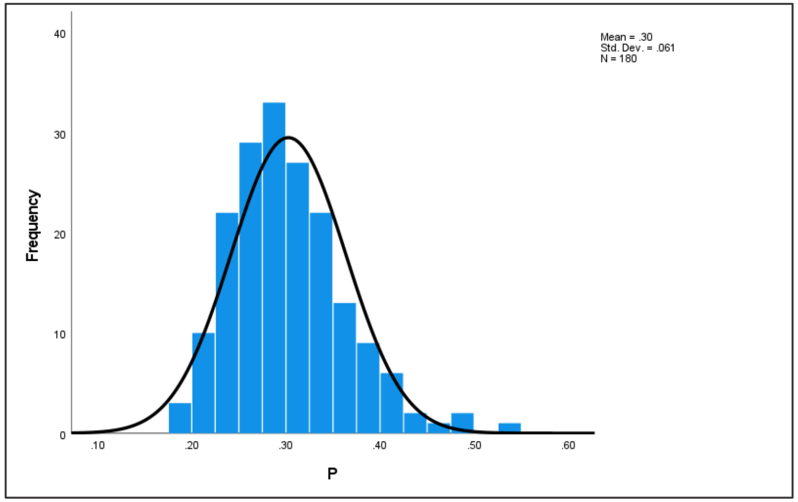


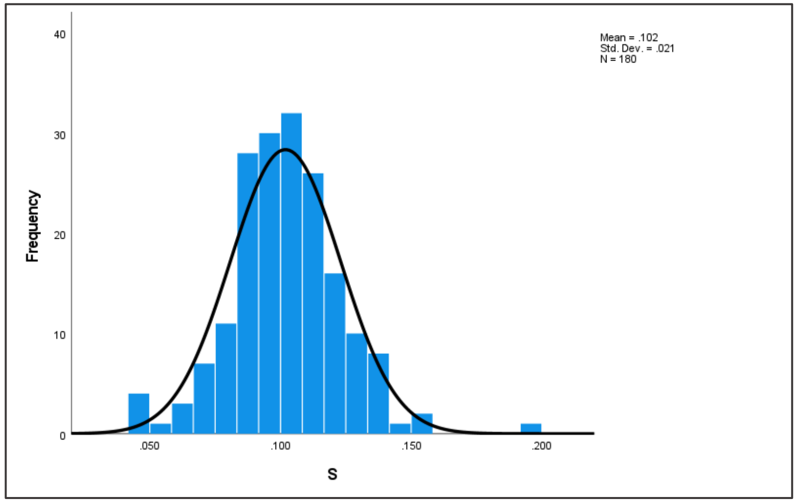


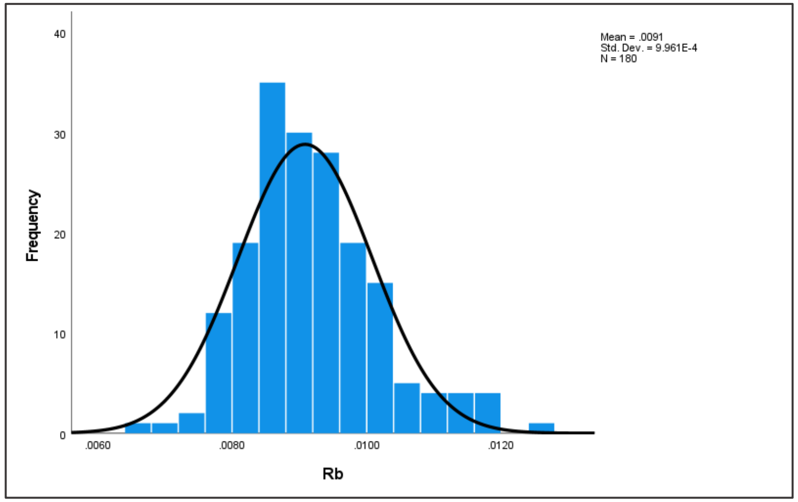

Mean = 4.61
Std. Dev. = .40
N = 180
Frequency
Fe

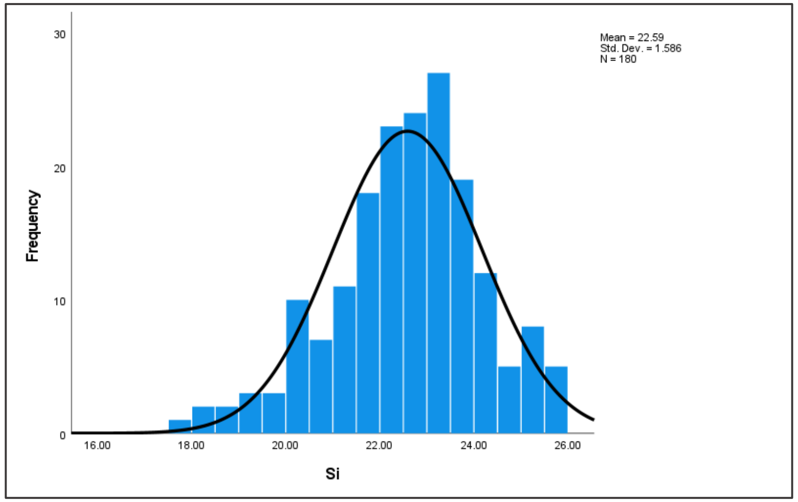

Mean = 1.96
Std. Dev. = .145
N = 180
Frequency
K

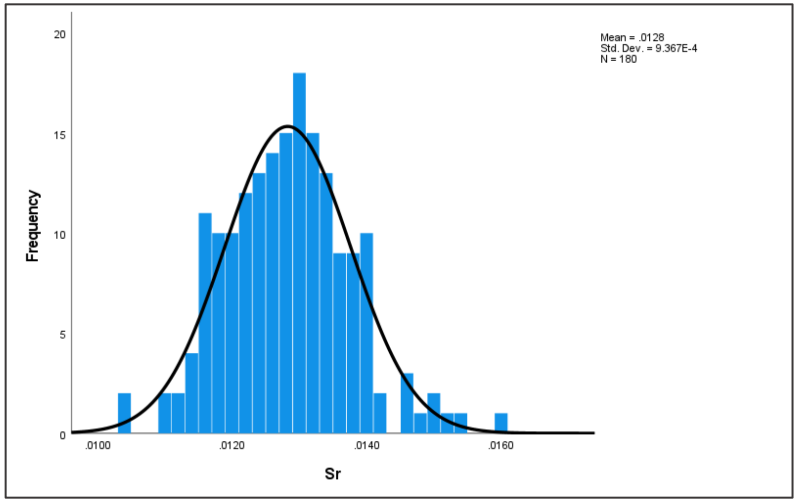

Mean = .11
Std. Dev. = .084
N = 180
Frequency
Mn

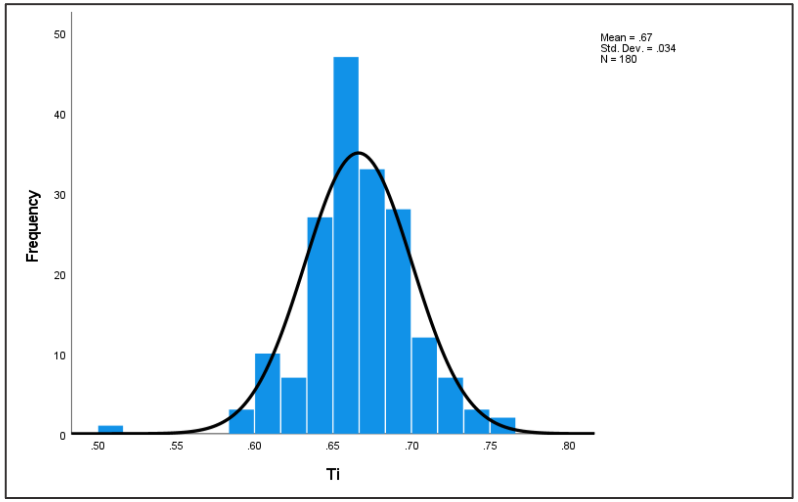

Mean = .30
Std. Dev. = .061
N = 180
Frequency
P

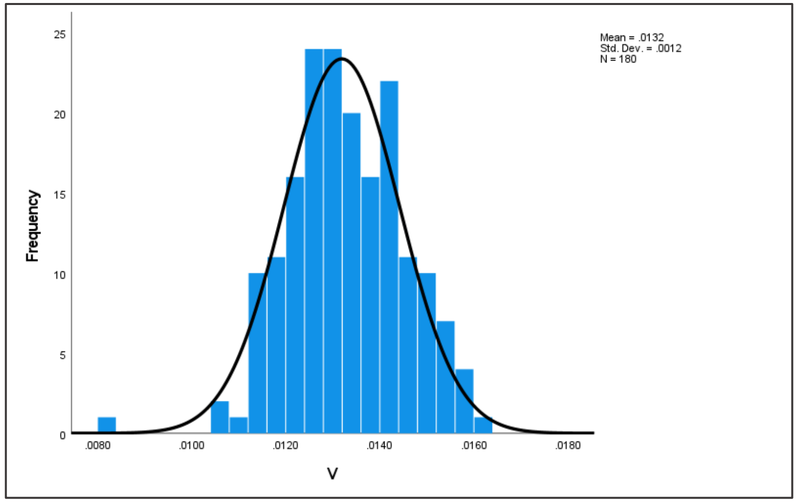

Mean = .102
Std. Dev. = .021
N = 180
Frequency
S

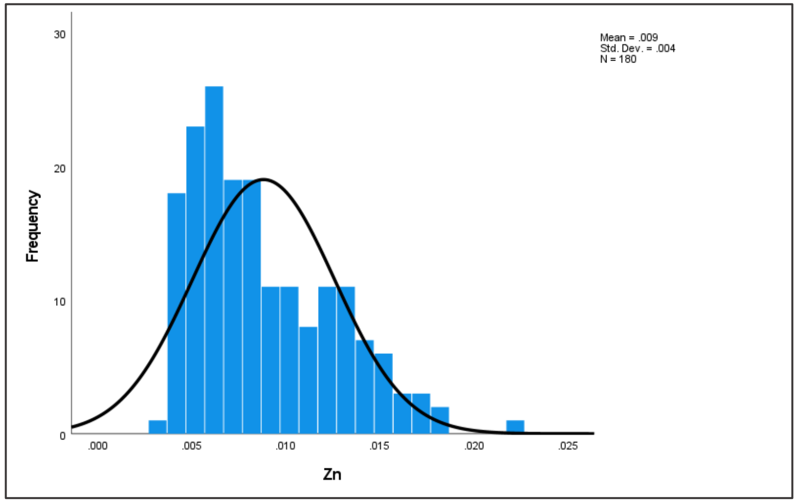

Mean = .0091
Std. Dev. = 9.961E-4
N = 180
Frequency
Rb

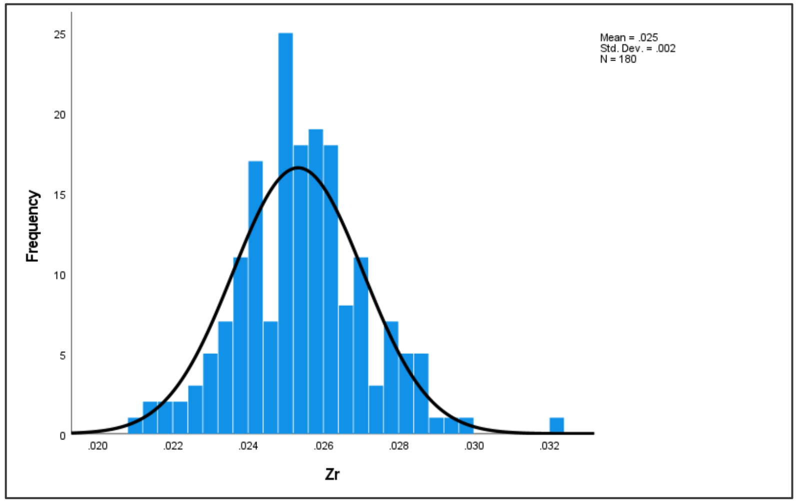

Mean = 22.59
Std. Dev. = 1.586
N = 180
Frequency
Si


Mean = .0128
Std. Dev. = 9.367E-4
N = 180
Frequency
Sr

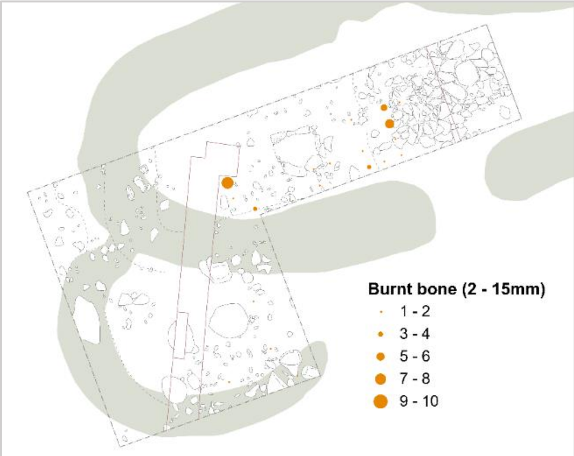

Mean = .67
Std. Dev. = .034
N = 180
Frequency
Ti

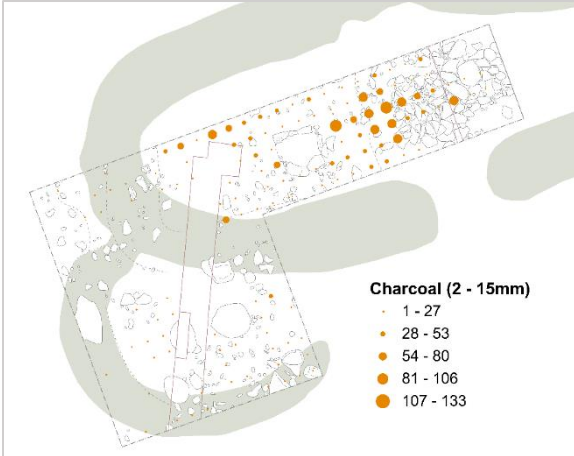

Mean = .0132
Std. Dev. = .0012
N = 180
Frequency
V

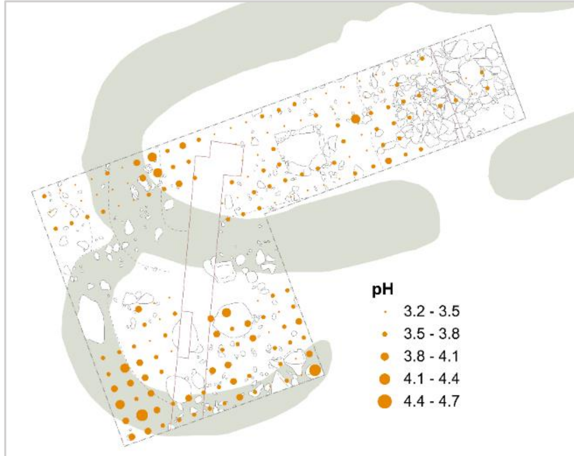

Mean = .009
Std. Dev. = .004
N = 180
Frequency
Zn

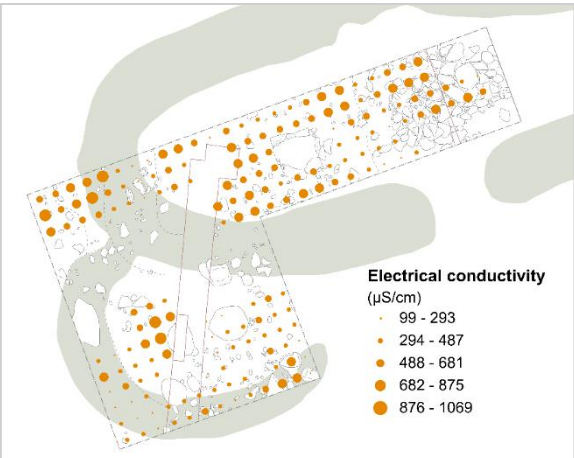

Mean = .025
Std. Dev. = .002
N = 180
Frequency
Zr

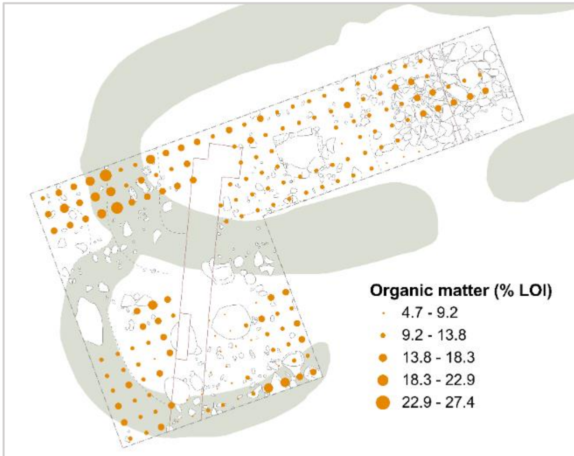
Sheet 7: Distribution of microrefuse, geochemical and magnetic variables

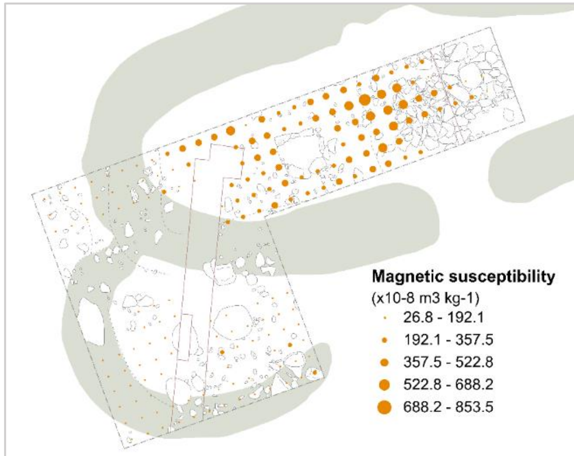




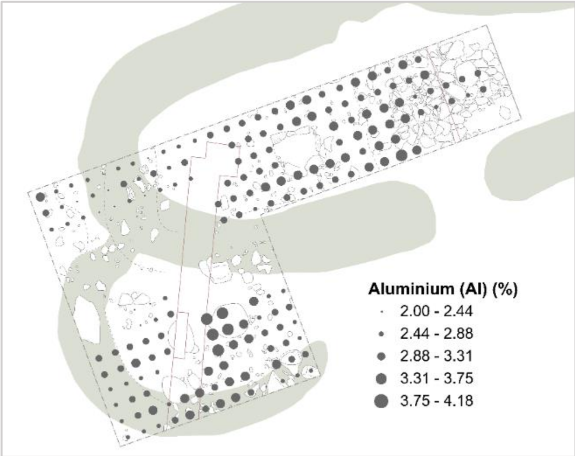


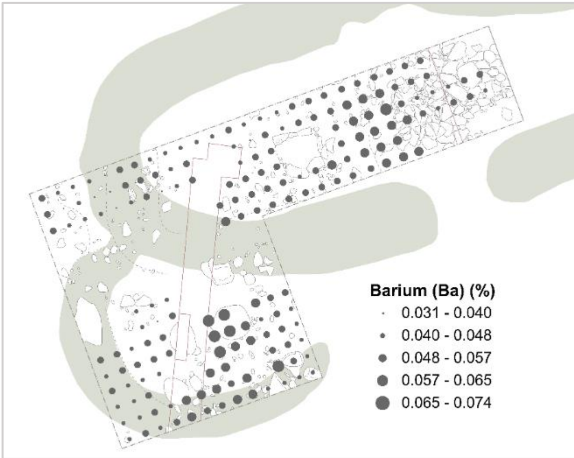


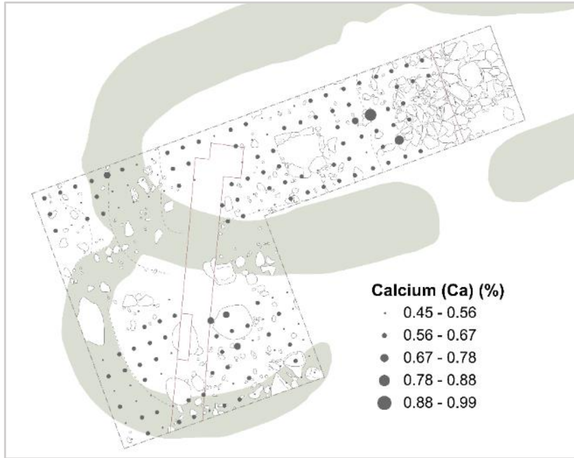


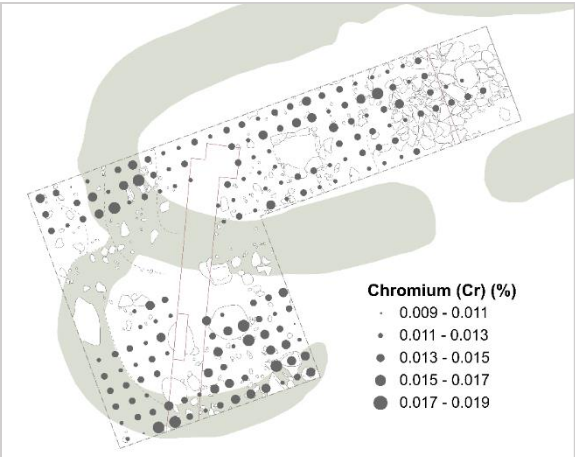


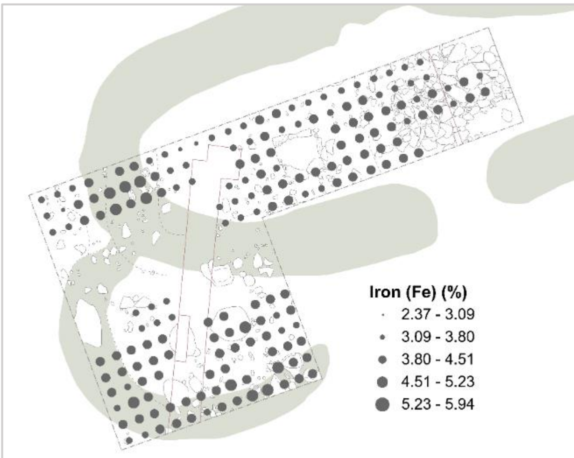
Sheet 8: Distribution of multi-element variables

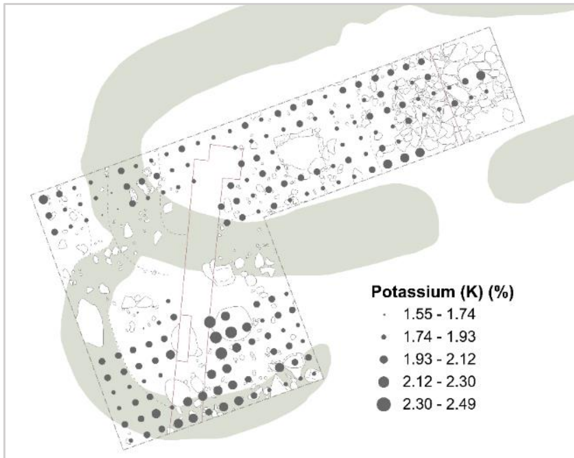


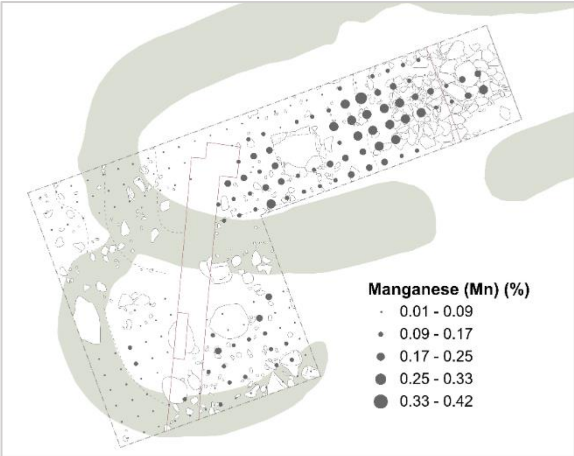


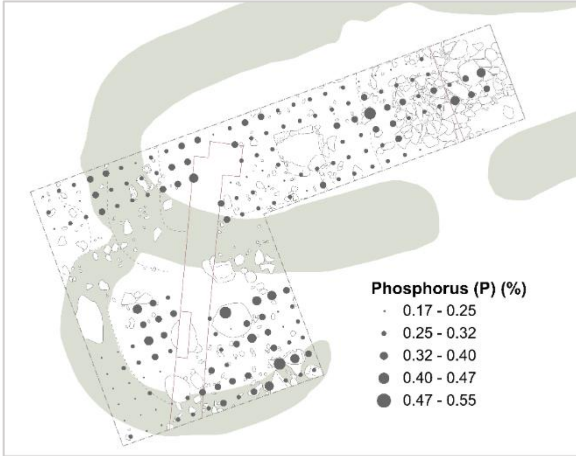


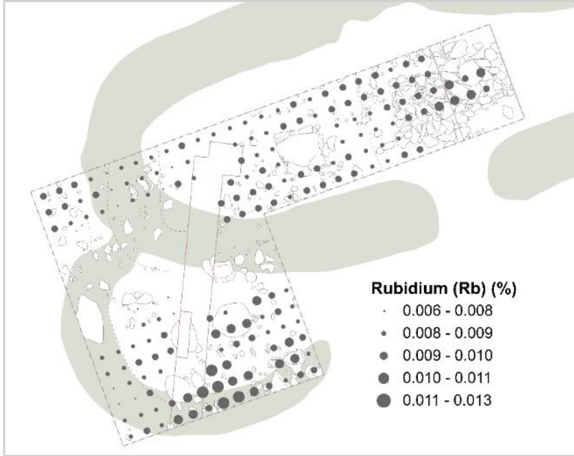


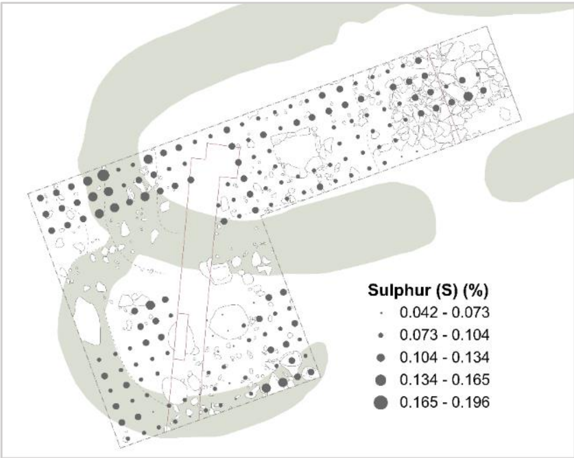


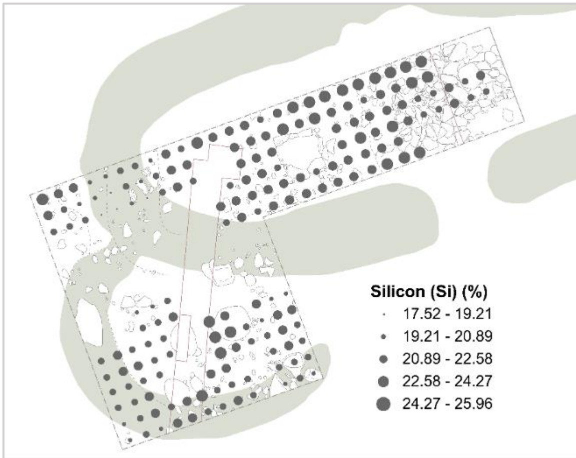


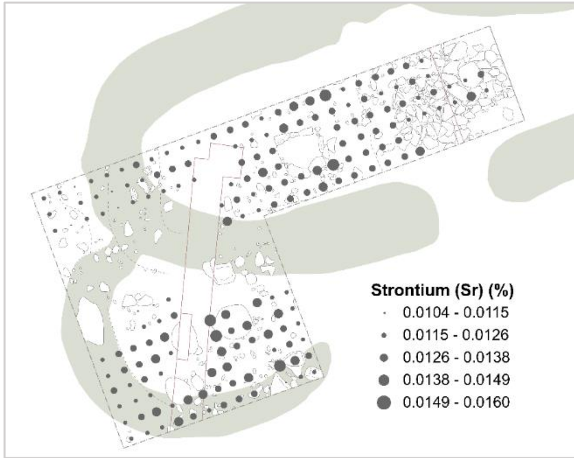

Manganese (Mn) (%)
0.01 - 0.09
0.09 - 0.17
0.17 - 0.25
0.25 - 0.33
0.33 - 0.42

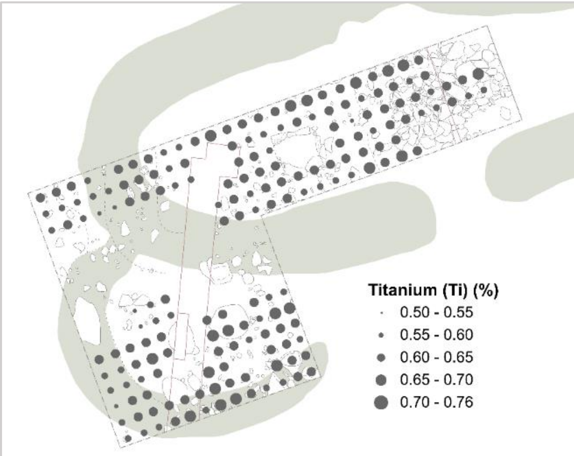

Phosphorus (P) (%)
0.17 - 0.25
0.25 - 0.32
0.32 - 0.40
0.40 - 0.47
0.47 - 0.55

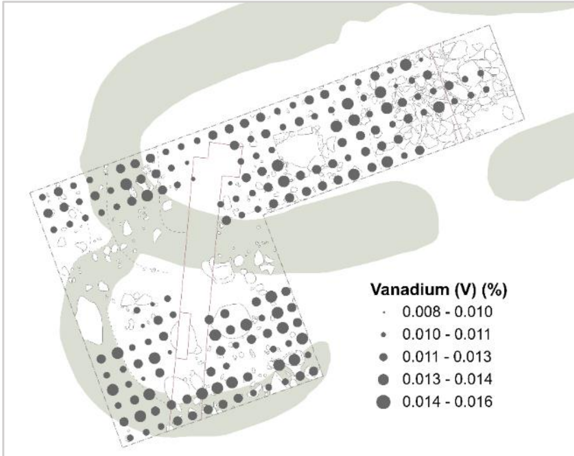

Rubidium (Rb) (%)
0.006 - 0.008
0.008 - 0.009
0.009 - 0.010
0.010 - 0.011
0.011 - 0.013

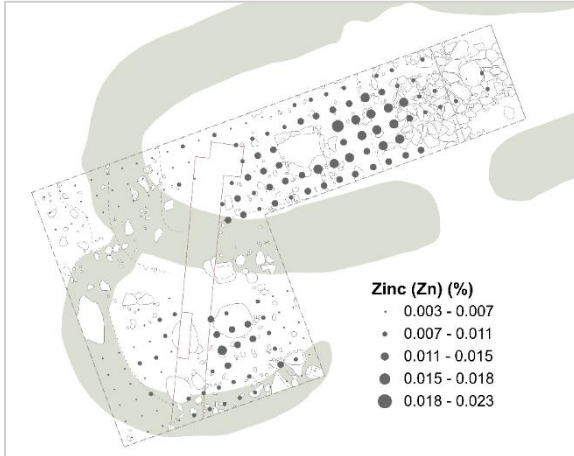

Sulphur (S) (%)
0.042 - 0.073
0.073 - 0.104
0.104 - 0.134
0.134 - 0.165
0.165 - 0.196

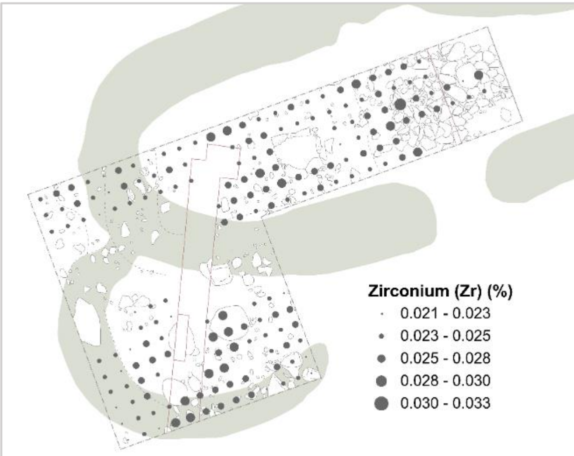

Silicon (Si) (%)
17.52 - 19.21
19.21 - 20.89
20.89 - 22.58
22.58 - 24.27
24.27 - 25.96


Strontium (Sr) (%)
0.0104 - 0.0115
0.0115 - 0.0126
0.0126 - 0.0138
0.0138 - 0.0149
0.0149 - 0.0160


Titanium (Ti) (%)
0.50 - 0.55
0.55 - 0.60
0.60 - 0.65
0.65 - 0.70
0.70 - 0.76


Vanadium (V) (%)
0.008 - 0.010
0.010 - 0.011
0.011 - 0.013
0.013 - 0.014
0.014 - 0.016


Zinc (Zn) (%)
0.003 - 0.007
0.007 - 0.011
0.011 - 0.015
0.015 - 0.018
0.018 - 0.023


Zirconium (Zr) (%)
0.021 - 0.023
0.023 - 0.025
0.025 - 0.028
0.028 - 0.030
0.030 - 0.033

SM1: Micromorphology locations, descriptions and interpretations

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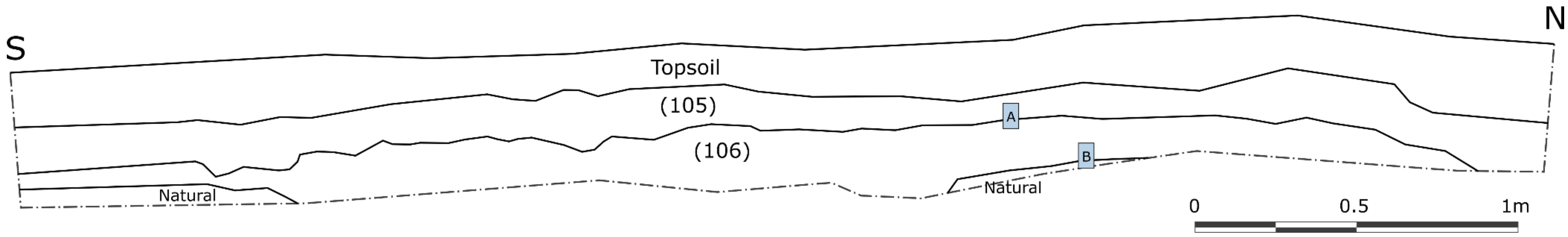
Supplementary Material x; Figure 1 Section drawing and photographs - thin-section locations; BHF16-A, BHF16-B



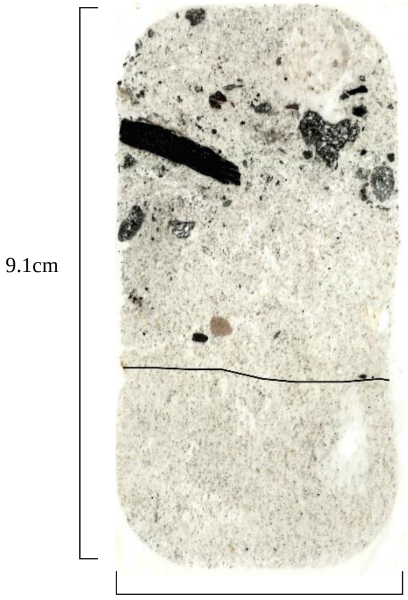
Supplementary Material x; Table 1.1 BHF16-A: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary**	Structure					Void Type*			Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels	Simple Packing Voids	Complex Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
105	58 mm	Diffuse	Medium-course sand	Intergrain microaggregate	Enaulic and chitonic	92:8	25	▪▪▪▪▪		▪▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Very dark brown; black	Undifferentiated
106	35 mm	Bottom of slide	Medium-course sand	Intergrain microaggregate	Enaulic and chitonic	96:4	29	▪▪▪▪▪	▪	▪▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Very dark brown; black	Undifferentiated

Context and Microstratigraphic Unit	Organic Matter						Inclusions					Pedofeatures	
	Charred			*Uncharred*									
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Wood Ash	Rubified Fine Mineral Material	Fabric Type 1 (Clay)	Fabric Type 2 (Clayey-Silt)	Fabric Type 3 (Very Fine Quartz Sand)	Fe /Mn	Excremental
105	▪▪▪	▪▪▪	▪▪	▪	+	▪▪	▪	▪	▪▪			+	▪▪
106			+	+	+	▪▪				▪	▪	+	▪▪

\+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)
** lower boundary described using the following definitions - **knife edge** (razor sharp), **sharp** (very clear and abrupt change), **clear** (transition occurs over less than 1cm), **diffuse** (transition is greater than 1cm) and **bottom of slide** (lower boundary of layer extends beyond base of thin-section);

Supplementary Material x; Table 1.2 BHF16-A: Thin-section interpretation



Context	Summary of key features	Interpretation
105	Medium-course sub-rounded quartz and feldspar beach sand (grain size 0.4–1.5 mm) containing organic intergrain microaggregates and multiple anthropogenic inclusions. Layer has the highest charred organic matter content for any sample taken across the site, with larger and more frequent fragments of wood (max. 4 x 21 mm; wood component includes pine) and plant matter (inc. monocot stems). Presence of wood ash with calcium phosphate crystals formed in situ. Uncharred organic component includes strongly decomposed roots in channels and the occasional seed. Fe-Mn pedofeatures are primarily pseudomorphs of plant residues and amorphous organic material. Aggregates of Fabric Type 1, a grey (PPL) clay – greyish-yellow in (OIL) – with platy microstructure, parallel and subparallel planar voids (10% porosity), and a unistriated b-fabric (XPL). Also found coating large charcoal fragment (4 x 21 mm).	Microartefact-rich, illuviated and bioturbated surface within structure. Surface is almost completely bioturbated, with no surviving microstructure of a relic floor. Interpreted as remnant of later occupation surface (undated); possibly dumped material. Aggregates of Fabric Type 1 and clay-coated charcoal fragment may be evidence of wattle-and-daub, with the unistriated b-fabric resulting from a 'smearing' action. Anthropogenic inclusions are unique to this thin-section and unusually well preserved, given the extensive illuviation and bioturbation throughout. May represent different preservation conditions or anthropogenic activity in this area.
106	Medium-course sub-rounded quartz and feldspar beach sand (grain size 0.4–1.5 mm) with organic intergrain microaggregates. No anthropogenic inclusions other than trace charcoal. Decreasing organic matter and microaggregate concentrations down the profile. Two different fabric types, classed as inclusions: Fabric Type 2 – Localised aggregates of yellowish-brown (PPL) clayey-silt – yellow in (OIL) – with massive microstructure and speckled b-fabric (XPL). Fabric Type 3 - Loamy sand (primarily very angular quartz grains) with undifferentiated b-fabric. Localised, forming discrete aggregates and intercalations (around 1 mm thick).	Illuviated and extensively bioturbated surface within structure; no surviving microstructure of a relic floor. Interpreted as remnant of primary occupation surface. Source/nature of aggregates and different fabric types is unclear.

Supplementary Material x; Table 2.1 BHF16-B: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Structure					Void Type*			Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels	Simple Packing Voids	Complex Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
106	73 mm	Clear	Medium-course sand	Intergrain microaggregate	Enaulic and chitonic	98:2	36	▪▪▪▪▪	▪▪	▪▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Very dark brown; black	Undifferentiated
Natural	18 mm	Bottom of slide	Medium-course sand	Intergrain microaggregate with localised single-grain structure	Enaulic	98:2	41	▪▪▪▪▪▪▪	▪▪▪▪▪	▪▪▪▪▪▪	Brown; dark brown; dotted	Dark brown	Undifferentiated

Context and Microstratigraphic Unit	Organic Matter						Inclusions					Pedofeatures	
	Charred			*Uncharred*									
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Wood Ash	Rubified Fine Mineral Material	Fabric Type 1 (Clay)	Fabric Type 2 (Clayey-Silt)	Fabric Type 3 (Very Fine Quartz Sand)	Fe /Mn	Excremental
106	+		+	+	+	▪		+			▪▪		▪
Natural	+		+	+		▪		+			+		▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

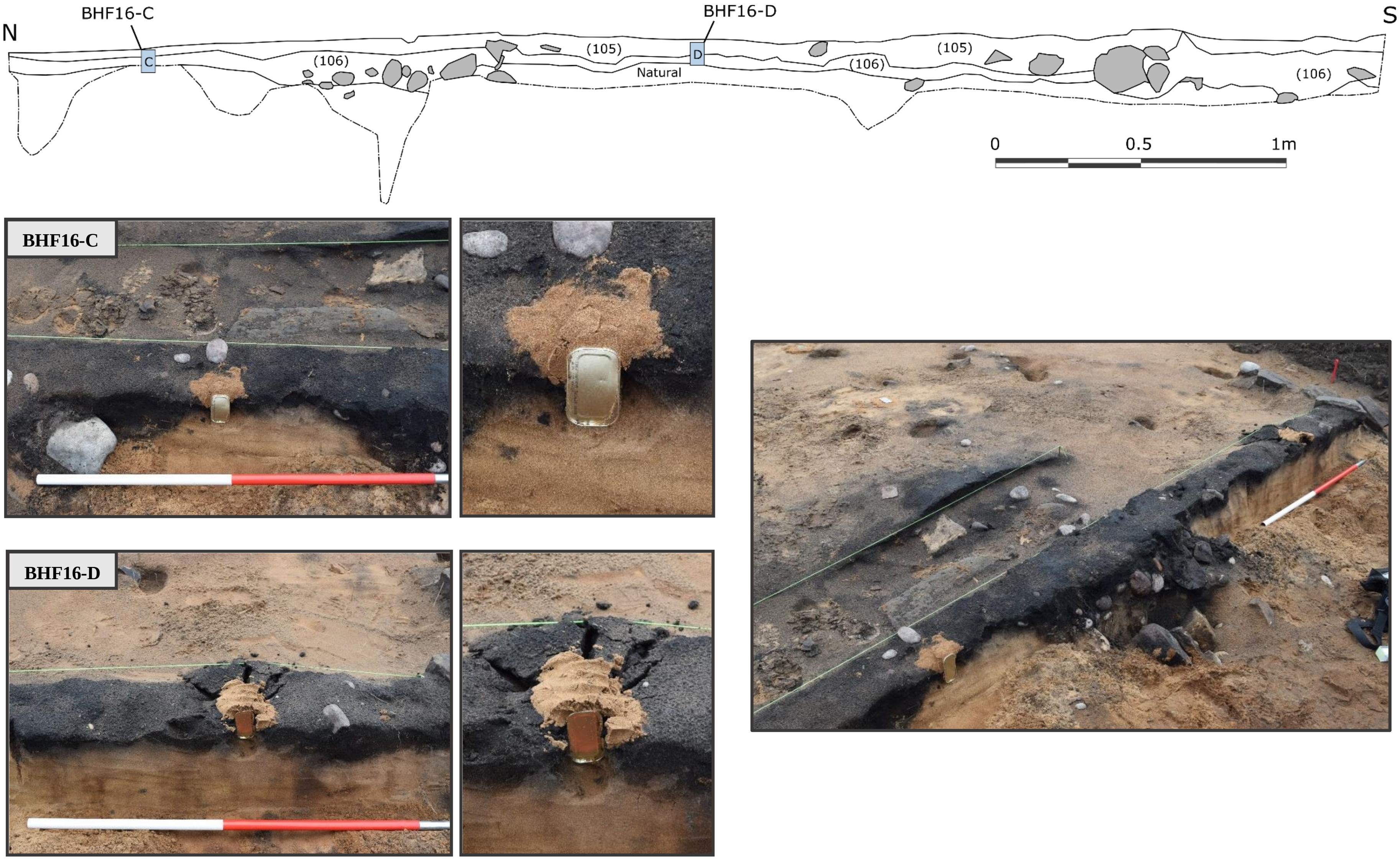
Supplementary Material x; Table 2.2 BHF16-B: Thin-section interpretation

9.2cm

4.5cm

Context	**Summary of key features**	**Interpretation**
106	Medium-course sub-rounded quartz and feldspar beach sand (grain size 0.4–1.5 mm) with organic intergrain microaggregates. No anthropogenic inclusions other than trace charcoal. Decreasing organic matter and microaggregate concentrations down the profile – less organic matter and fewer microaggregates in this lower section of (106) than in the higher (106) from BHF16-A. Slight increase in quantity of Fabric Type 3 compared to (106) in BHF16-A. Area of manufacturing error (thinning) towards base of layer, left-hand side.	Illuviated and extensively bioturbated surface within structure; no surviving microstructure of a relic floor. Interpreted as remnant of primary occupation surface. Source/nature of aggregates and different fabric types is unclear.
Natural	Medium-course sub-rounded quartz and feldspar sand. No anthropogenic inclusions other than trace charcoal and illuviated material from layers above. More organic matter and microaggregates in this example of 'natural' than in other sampled areas – likely reflects higher quantity of material in (105) and (106). Large channel (20 x 4 mm) and area of manufacturing error (thinning) towards base of slide.	Non-sterile sand subsoil (disturbed by filled and partially infilled earthworm channels, illuviated organic material and trace charcoal).

Supplementary Material x; Figure 2 Section drawing and photographs - thin-section locations; BHF16-C, BHF16-D



Supplementary Material x; Table 3.1 BHF16-C: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	**Structure**					**Void Type***			**Fine Material**		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels	Simple Packing Voids	Complex Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
Packing sand**	2 mm	Sharp											
105	22 mm	Diffuse	Medium-course sand	Intergrain microaggregate with localised pellicular structure	Enaulic and chitonic	93:7	25	▪▪▪▪	▪	▪▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Very dark brown; black	Undifferentiated
106	48 mm	Clear	Medium-course sand	Intergrain microaggregate with localised pellicular structure	Enaulic and chitonic	97:3	30	▪▪▪▪	▪▪▪▪	▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Very dark brown; black	Undifferentiated
Natural	22 mm	Bottom of slide	Medium-course sand	Single-grain structure with localised intergrain microaggregate	Localised enaulic	99:1	30	▪▪▪▪	▪▪▪▪▪▪▪▪	▪▪▪▪▪	Dark brown; dotted	Dark brown	Undifferentiated

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)

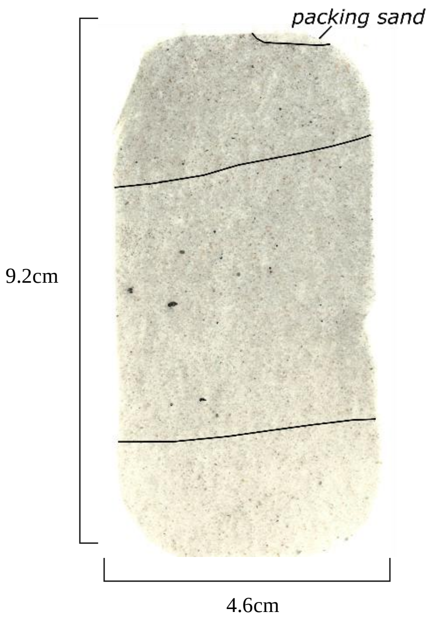
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

** samples BHF16-C to BHF16-G were taken using a yellow packing-sand to secure the loose fill of the blocks; under the microscope, this packing sand is recognised by significantly less organic matter and does not display the same intergrain microaggregate microstructure of (1005) and (1010)

Context and Microstratigraphic Unit	Organic Matter						Inclusions					Pedofeatures	
	Charred			*Uncharred*									
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Wood Ash	Rubified Fine Mineral Material	Fabric Type 1 (Clay)	Fabric Type 2 (Clayey-Silt)	Fabric Type 3 (Very Fine Quartz Sand)	Fe /Mn	Excremental
Packing sand													
105	+	+	▪	+		▪▪							▪▪
106	+	▪	▪	▪	+	▪▪		+				+	▪
Natural	+		+	+		▪							+

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

Supplementary Material x; Table 3.2 BHF16-C: Thin-section interpretation



Context	Summary of key features	Interpretation
105	Medium-course sub-rounded quartz and feldspar beach sand (grain size 0.4–1.5 mm) containing organic intergrain microaggregates. Organic coatings of sand grains (chitonic distribution) in addition to microaggregate microstructure indicates extensive illuviation and bioturbation. Decreasing organic matter and microaggregate concentrations down the profile. No anthropogenic inclusions other than trace charcoal.	Extensively illuviated and bioturbated surface within structure. Surface is almost completely bioturbated, with no surviving microstructure of a relic floor. Interpreted as remnant of later occupation surface (undated).
106	Medium-course sub-rounded quartz and feldspar beach sand (grain size 0.4–1.5 mm) containing organic coatings and intergrain microaggregates. Higher porosity and fewer microaggregates/coatings than (105), particularly towards base of layer. No anthropogenic inclusions other than trace charcoal.	Extensively illuviated and bioturbated surface within structure; no surviving microstructure of a relic floor. Interpreted as remnant of primary occupation surface.
Natural	Medium-course sub-rounded quartz and feldspar sand. No anthropogenic inclusions other than trace charcoal and illuviated organic material.	Non-sterile sand subsoil (disturbed by earthworm channels, illuviated organic material and trace charcoal).

Supplementary Material x; Table 4.1 BHF16-D: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Structure					Void Type*			Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels	Simple Packing Voids	Complex Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
Packing sand	11 mm	Clear											
105	38 mm	Diffuse; undulating	Medium-course sand	Intergrain microaggregate with localised pellicular structure	Enaulic and chitonic	93:7	25	▪▪▪▪	▪▪	▪▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Very dark brown; black	Undifferentiated
106	22 mm	Clear	Medium-course sand	Intergrain microaggregate with localised pellicular structure	Enaulic and chitonic	97:3	35	▪▪▪▪▪	▪▪▪▪	▪▪▪▪▪▪▪▪▪	Very dark brown; black; dotted	Very dark brown; black	Undifferentiated
Natural	12 mm	Bottom of slide	Medium-course sand	Single-grain structure with localised intergrain microaggregate	Localised enaulic	99:1	30	▪▪▪▪	▪▪▪▪▪▪▪▪	▪▪▪▪▪	Dark brown; dotted	Dark brown	Undifferentiated

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)

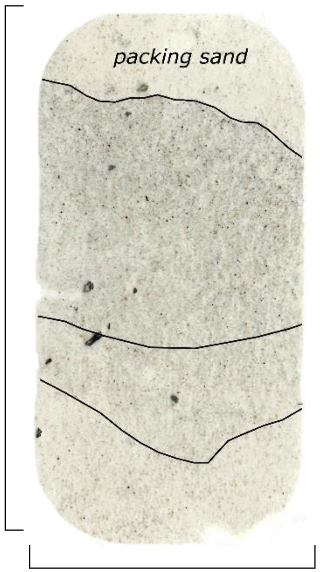
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

Context and Microstratigraphic Unit	Organic Matter						Inclusions					Pedofeatures	
	Charred			*Uncharred*									
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Wood Ash	Rubified Fine Mineral Material	Fabric Type 1 (Clay)	Fabric Type 2 (Clayey-Silt)	Fabric Type 3 (Very Fine Quartz Sand)	Fe /Mn	Excremental
Packing sand													
105	▪	+	▪	+	+	▪▪▪							▪▪▪
106	▪		+	+	+	▪▪							▪▪
Natural	+		+	+		▪							+

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

Supplementary Material x; Table 4.2 BHF16-D: Thin-section interpretation

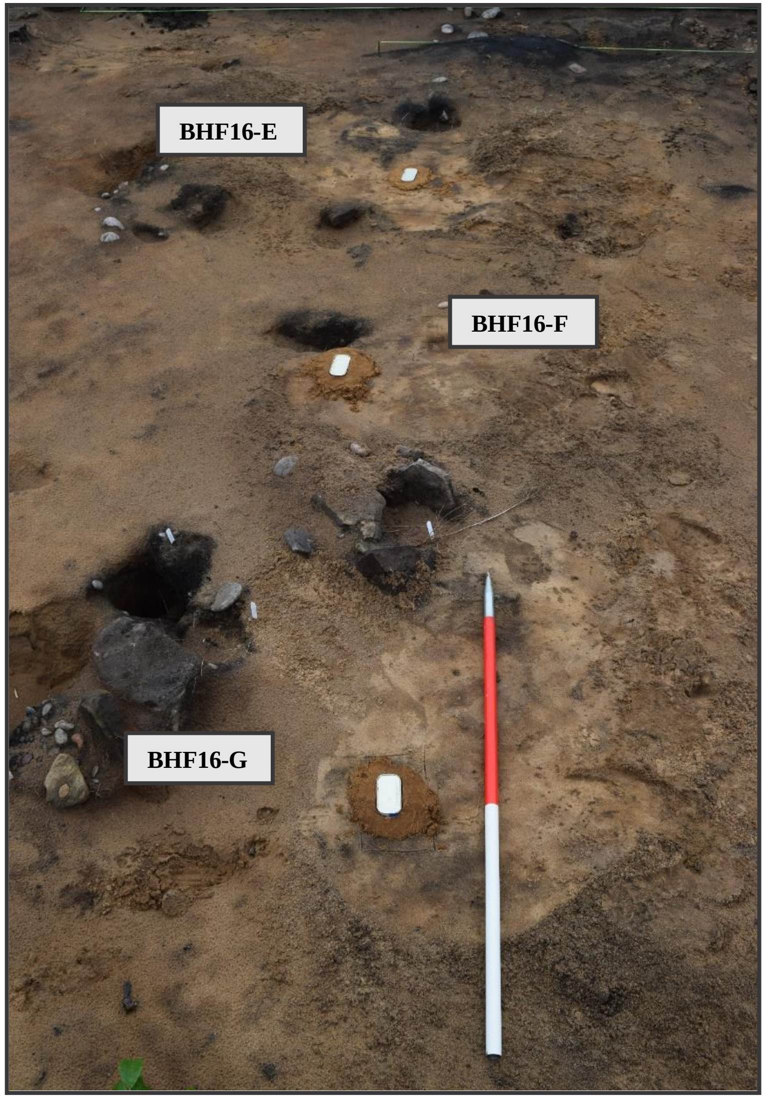
9.2cm



4.6cm

Context	Summary of key features	Interpretation
105	Medium-course sub-rounded quartz and feldspar beach sand (grain size 0.4–1.5 mm) containing organic intergrain microaggregates. Organic coatings of sand grains (chitonic distribution) in addition to microaggregate microstructure indicates extensive illuviation and bioturbation. Decreasing organic matter and microaggregate concentrations down the profile. No anthropogenic inclusions other than trace charcoal.	Extensively illuviated and bioturbated surface within structure. Surface is almost completely bioturbated, with no surviving microstructure of a relic floor. Interpreted as remnant of later occupation surface (undated).
106	Medium-course sub-rounded quartz and feldspar beach sand (grain size 0.4–1.5 mm) containing organic coatings and intergrain microaggregates. Higher porosity and fewer microaggregates/coatings than (105), particularly towards base of layer. No anthropogenic inclusions other than trace charcoal.	Extensively illuviated and bioturbated surface within structure; no surviving microstructure of a relic floor. Interpreted as remnant of primary occupation surface.
	Medium-course sub-rounded quartz and feldspar sand. No anthropogenic inclusions other than trace charcoal and illuviated organic material.	Non-sterile sand subsoil (disturbed by earthworm channels, illuviated organic material and trace charcoal).

Supplementary Material x; Figure 3 Plan photographs (with and without annotations) - thin-section locations; BHF16-E, BHF16-F, BHF16-G



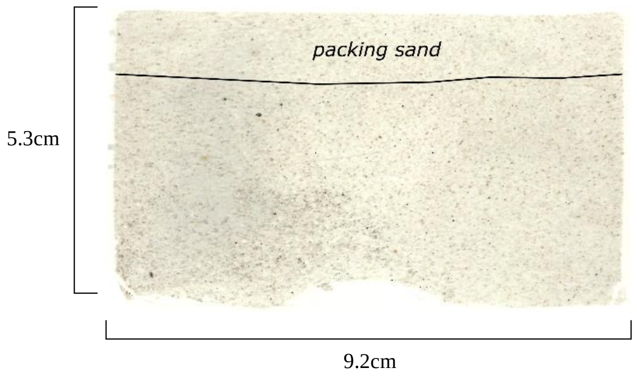
Supplementary Material x; Table 5.1 BHF16-E: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Structure: Textural Class	Structure: Microstructure	Structure: Course/Fine (100µm) Related Distribution	Structure: Course:Fine (100µm) Ratio	Structure: Porosity (%)	Void Type*: Channels	Void Type*: Simple Packing Voids	Void Type*: Complex Packing Voids	Fine Material: Nature of Fine Material (PPL)	Fine Material: Colour of Fine Material (OIL)	Fine Material: Birefringence Fabric (XPL)
Packing sand	15 mm	Knife-edge											
106	40 mm	Bottom of slide	Medium-course sand	Intergrain microaggregate with localised single-grain structure	Enaulic	97:3	30	▪▪▪	▪▪▪▪▪▪▪▪	▪▪▪▪▪▪	Dark brown; dotted	Dark brown	Undifferentiated

Context and Microstratigraphic Unit	Organic Matter: Charred: Wood (Charcoal)	Organic Matter: Charred: Plant	Organic Matter: Charred: Amorphous Organic Matter	Organic Matter: Uncharred: Plant	Organic Matter: Uncharred: Fungal Sclerotia	Organic Matter: Uncharred: Amorphous Organic Matter	Inclusions: Wood Ash	Inclusions: Rubified Fine Mineral Material	Inclusions: Fabric Type 1 (Clay)	Inclusions: Fabric Type 2 (Clayey-Silt)	Inclusions: Fabric Type 3 (Very Fine Quartz Sand)	Pedofeatures: Fe /Mn	Pedofeatures: Excremental
Packing sand													
106		+	+	▪	+	▪▪							▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

Supplementary Material x; Table 5.2 BHF16-E: Thin-section interpretation



Context	Summary of key features	Interpretation
106	Medium-course sub-rounded quartz and feldspar beach sand (grain size 0.4–1.5 mm); almost completely bioturbated with any surviving fabric existing solely as intergrain microaggregates/excremental pedofeatures that are associated with areas of looser infilled material. No anthropogenic inclusions other than trace charcoal and plant matter (max. 360 x 200µm). Presence of fresh and moderately decomposed roots and seeds (max. 500 x 360µm). Large, partially-filled channel at left-hand side of slide (recognised by looser nature of infilled material) accounts for around 10% of captured area - avoided during quantification.	Illuviated and almost completely bioturbated surface with no surviving microstructure of a relic floor.

Supplementary Material x; Table 6.1 BHF16-F: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Structure					Void Type*			Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels	Simple Packing Voids	Complex Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
Packing sand	10 mm	Clear											
106	43 mm	Bottom of slide	Medium-course sand	Single-grain structure with localised intergrain microaggregate	Enaulic	99:1	30	▪▪	▪▪▪▪▪▪▪▪	▪▪▪▪▪▪▪	Dark brown; dotted	Dark brown	Undifferentiated

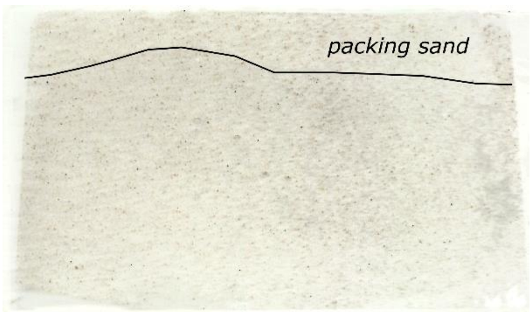
Context and Microstratigraphic Unit	Organic Matter						Inclusions					Pedofeatures	
	Charred			*Uncharred*									
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Wood Ash	Rubified Fine Mineral Material	Fabric Type 1 (Clay)	Fabric Type 2 (Clayey-Silt)	Fabric Type 3 (Very Fine Quartz Sand)	Fe /Mn	Excremental
Packing sand													
106			+	+	+	▪							▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

Supplementary Material x; Table 6.2

BHF16-F: Thin-section interpretation

4.9cm



8..4cm

Context	Summary of key features	Interpretation
106	Medium-course sub-rounded quartz and feldspar beach sand (grain size 0.4–1.5 mm); almost completely bioturbated with any surviving fabric existing solely as intergrain microaggregates/excremental pedofeatures. Similar composition to BHF16-E and BHF16-G but with far fewer microaggregates and less organic matter. Areas of highest microaggregate concentration associated with channel infillings. No anthropogenic inclusions other than trace charcoal. Presence of strongly decomposed roots. Various areas of slide thinned and abraded by manufacturing (evidenced by quartz fracturing) - areas avoided where possible during quantification.	Illuviated and almost completely bioturbated surface with no surviving microstructure of a relic floor.

Supplementary Material x; Table 7.1 BHF16-G: Thin-section description

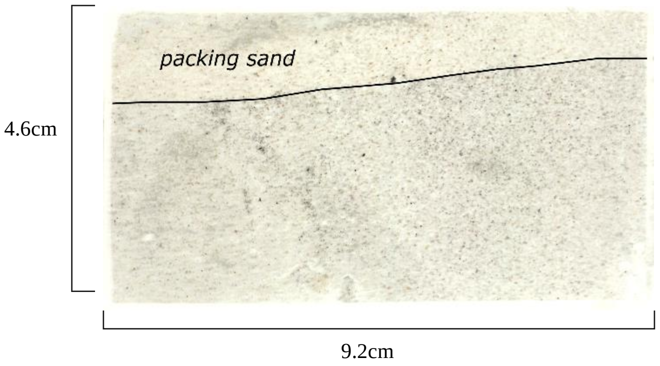
Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary	Structure					Void Type*			Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels	Simple Packing Voids	Complex Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
Packing sand	19 mm	Knife-edge											
106	39 mm	Bottom of slide	Medium-course sand	Intergrain microaggregate	Enaulic	96:4	25	▪▪▪▪	▪▪▪▪	▪▪▪▪▪▪▪▪▪▪	Dark brown; dotted	Dark brown	Undifferentiated

Context and Microstratigraphic Unit	Organic Matter						Inclusions					Pedofeatures	
	Charred			Uncharred									
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Wood Ash	Rubified Fine Mineral Material	Fabric Type 1 (Clay)	Fabric Type 2 (Clayey-Silt)	Fabric Type 3 (Very Fine Quartz Sand)	Fe /Mn	Excremental
Packing sand													
106	+	+	+	▪	+	▪▪							▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

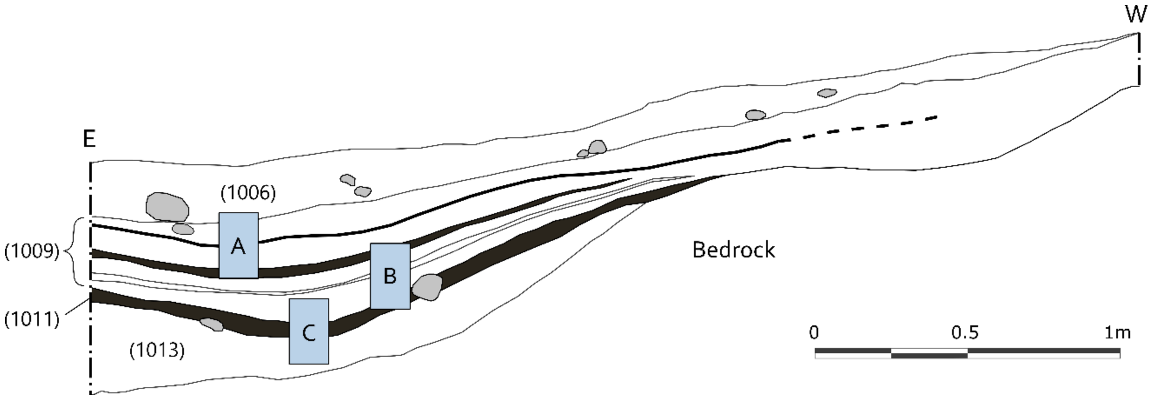
Supplementary Material x; Table 7.2

BHF16-G: Thin-section interpretation



Context	Summary of key features	Interpretation
106	Medium-course sub-rounded quartz and feldspar beach sand (grain size 0.4–1.5 mm); almost completely bioturbated with any surviving fabric existing solely as intergrain microaggregates/excremental pedofeatures. Similar composition to BHF16-E and BHF16-G but a higher concentration of microaggregates and organic matter. Areas of highest microaggregate concentration associated with channel infillings. No anthropogenic inclusions other than trace charcoal. Presence of strongly decomposed roots. Various areas of slide thinned and abraded by manufacturing (evidenced by quartz fracturing) - areas avoided where possible during quantification.	Illuviated and almost completely bioturbated surface with no surviving microstructure of a relic floor. Possible remnant of earlier structure associated with postholes.

Supplementary Material x; Figure 1 Section drawing and photographs - thin-section locations; DUNC16-A, DUNC16-B, DUNC16-C



Notes:

- Location of removed tins can be seen in right image
- Tin C (in right image) has been relabelled 'B' for analysis and in section drawing (left), on account of location in soil profile

Supplementary Material x; Table 1.1 DUNC16-A: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary**	Structure					Void Type*				Fine Material		
			Textural Class	Microstructure	Course/Fine (100μm) Related Distribution	Course:Fine (100μm) Ratio	Porosity (%)	Channels and Vughs	Planar (Random)	Planar (Horizontal)	Compound Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
1006	2 mm	Clear												
1009.1	15 mm	Clear	Organic sandy silt loam	Weakly to moderately developed subangular blocky with channels	Porphyric; unevenly distributed close to open porphyric	55:45	25	▪▪▪▪▪▪▪▪▪▪	▪▪▪			Orangish-brown; dotted	Orangish-yellow	Stipple-speckled
1009.2	45 mm	Sharp	Organic sandy silt loam	Moderately developed subangular blocky with channels and horizontal planar voids	Porphyric; unevenly distributed close to open porphyric	40:60	15	▪▪▪▪▪▪▪▪▪	▪▪▪▪	▪▪▪▪	▪	Orangish-brown; mid-brown; dotted	Orangish-yellow; brownish-yellow	Stipple-speckled
1009.3	15 mm	Sharp	Very organic sandy silt loam	Well-developed subangular blocky with intra-aggregate crumb structure and channels	Porphyric; unevenly distributed close to open porphyric	35:65	10	▪▪▪▪▪▪▪	▪▪▪▪▪▪▪	▪	▪▪▪	Orangish-brown; dark brown; dotted	Yellowish-brown; dark brown	Stipple-speckled; localised undifferentiated
1009.4	6 mm	Bottom of slide												

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)

* frequency class for voids refers to % total void space (following Bullock et al. 1985)

** lower boundary described using the following definitions - **knife edge** (razor sharp), **sharp** (very clear and abrupt change), **clear** (transition occurs over less than 1cm), **diffuse** (transition is greater than 1cm) and **bottom of slide** (lower boundary of layer extends beyond base of thin-section); modifiers such as **incline** also used to define their character

Context and Microstratigraphic Unit	Organic Matter						Inclusions		Pedofeatures	
	Charred			*Uncharred*						
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Rubified Fine Mineral Material	Intrusive Aggregates	Fe/Mn	Excremental
1006										
1009.1	▪▪▪	+	▪▪	▪	+	▪▪▪▪	▪		▪	▪▪
1009.2	▪	+	▪	▪	+	▪▪▪▪	+	+	▪	▪▪
1009.3	▪▪▪	+	▪▪		+	▪▪▪▪▪▪			▪	▪▪
1009.4										

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)
** lower boundary described using the following definitions - **knife edge** (razor sharp), **sharp** (very clear and abrupt change), **clear** (transition occurs over less than 1cm), **diffuse** (transition is greater than 1cm) and **bottom of slide** (lower boundary of layer extends beyond base of thin-section); modifiers such as **incline** also used to define their character

Supplementary Material x; Table 1.2 DUNC16-A: Thin-section interpretation

Context	Summary of key features	Interpretation
1006	Captured at top of thin-section but lost during manufacturing process; not enough remaining material for quantification or analysis.	n/a
1009.1	Organic sandy silt loam with weakly to moderately developed subangular blocky microstructure, organic acid pigmentation and occasional horizontal orientation of charcoal and minerals. No anthropogenic inclusions other than charcoal Charred wood component includes fragments from birch/willow family. Uncharred plant material composed of moderately to very strongly decomposed roots. Around 30% of what was captured in thin-section was disturbed by a large, partially-infilled earthworm channel; this area was avoided during quantification.	Occupation surface with evidence of bioturbation. One of a series of layers of material built up over time and deposited during use of structure in lower terrace. Lack of anthropogenic inclusions may have resulted from maintenance practices, in addition to post-depositional processes.
1009.2	Organic sandy silt loam with moderately developed subangular blocky microstructure, organic acid pigmentation and horizontal planar voids (10-20%). Anthropogenic inclusions limited to small quantity of charcoal (<2%) and a cluster of strongly decomposed circular organic material, which may represent something similar to degraded leather (exact material type unknown). Charred wood component includes hazel and birch/willow family; uncharred plant component composed of strongly to very strongly decomposed roots and a single seed head. Around 25% of what was captured in thin-section was disturbed by a large earthworm channel, partially-infilled with excremental pedofeatures and smaller soil aggregates; this area was avoided during quantification.	Occupation surface (floor) with evidence of compaction and trampling. One of a series of layers deposited during use of structure in lower terrace. Lack of anthropogenic inclusions may have resulted from maintenance practices, in addition to post-depositional processes.
1009.3	Highly organic sandy silt loam with well-developed and well-accommodating subangular blocky microstructure, intra-aggregate crumb structure and occasional weak horizontal distribution of charcoal. Localised undifferentiated b-fabric due to organic pigmentation. Charred wood component includes birch/willow family.	Organic matter-rich surface with evidence of bioturbation. One of a series of layers deposited during use of structure in lower terrace. Crumb structure may have been formed by biological activity or by the nature of the spread/dumped material. Lack of anthropogenic inclusions may have resulted from maintenance practices, in addition to post-depositional processes.
1009.4	Captured at base of thin-section. Appeared to show two distinct layers, with a boundary caused by a thin black layer overlying mineral, pores and the course/fine material. Interpreted as possible carborundum powder from the manufacturing process. Further investigation of 1009.4 in DUNC16-A was abandoned due to contamination and likelihood that the additional horizon was artificial and the result of manufacturing. 1009.4 was quantified and examined using DUNC16-B.	n/a

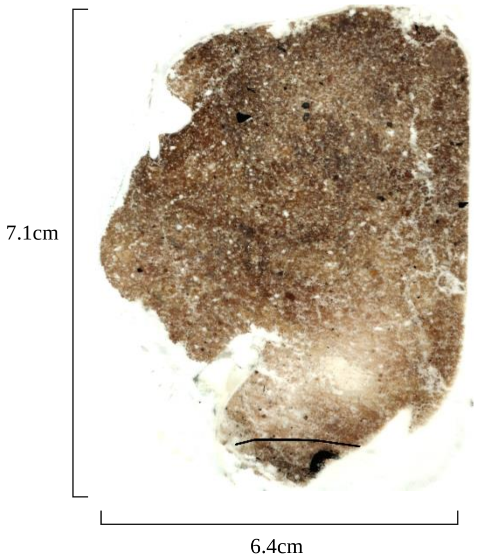
Supplementary Material x; Table 2.1 DUNC16-B: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary**	Structure: Textural Class	Structure: Microstructure	Structure: Course/Fine (100µm) Related Distribution	Structure: Course:Fine (100µm) Ratio	Structure: Porosity (%)	Void Type*: Channels and Vughs	Void Type*: Planar (Random)	Void Type*: Planar (Horizontal)	Void Type*: Compound Packing Voids	Fine Material: Nature of Fine Material (PPL)	Fine Material: Colour of Fine Material (OIL)	Fine Material: Birefringence Fabric (XPL)
1009.4	72 mm	Sharp	Organic sandy silt loam	Moderately to well-developed subangular blocky with intra-aggregate crumb structure and channels	Porphyric; unevenly distributed close to open porphyric	35:65	10	▪▪▪▪▪▪	▪▪▪▪▪▪▪▪		▪▪▪▪	Orangish-brown; dark brown; dotted	Yellowish-orange; dark brown	Stipple-speckled
1011	5 mm	Bottom of slide												

Context and Microstratigraphic Unit	Organic Matter: Charred: Wood (Charcoal)	Organic Matter: Charred: Plant	Organic Matter: Charred: Amorphous Organic Matter	Organic Matter: Uncharred: Plant	Organic Matter: Uncharred: Fungal Sclerotia	Organic Matter: Uncharred: Amorphous Organic Matter	Inclusions: Rubified Fine Mineral Material	Inclusions: Intrusive Aggregates	Pedofeatures: Fe/Mn	Pedofeatures: Excremental
1009.4	▪		▪	+	+	▪▪▪▪	+		+	▪▪
1011										

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)
** lower boundary described using the following definitions - **knife edge** (razor sharp), **sharp** (very clear and abrupt change), **clear** (transition occurs over less than 1cm), **diffuse** (transition is greater than 1cm) and **bottom of slide** (lower boundary of layer extends beyond base of thin-section); modifiers such as **incline** also used to define their character

Supplementary Material x; Table 2.2 DUNC16-B: Thin-section interpretation



Context	Summary of key features	Interpretation
1009.4	Organic sandy silt loam with moderately to well-developed subangular blocky microstructure and intra-aggregate crumb structure. No anthropogenic inclusions other than charcoal (max. 2.0 x 1.5 mm). Multiple sublinear areas of darker, more organic material with lower porosity (max. 27 x 3 mm) identified at 1:1 scale and under magnification. Short intercalations and nodules of Fe preferentially bonding with decomposed organic matter – dark bands and Fe features both occur predominantly in centre of layer. Worm and mite excrement present in channels; small, partially-infilled earthworm channel at top-right of slide avoided during quantification. Area of manufacturing error (thinning) towards base of layer; area avoided during quantification.	Bioturbated surface, forming one of a series of layers deposited in lower terrace structure. Sublinear compacted zones may be evidence of compaction and/or organic material, such as turf. Crumb structure could be remnant from turf A horizons. Possible evidence for levelling or rebuilding episode.
1011	Captured at base of thin-section but almost completely lost during manufacturing process; not enough remaining material for quantification or analysis. 1011 was quantified and examined using DUNC16-C.	n/a

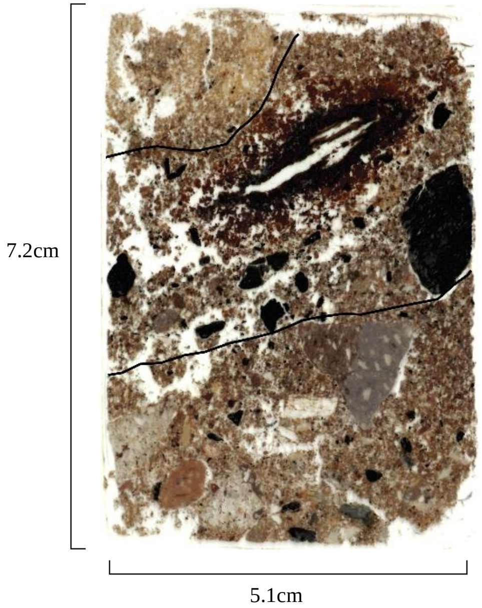
Supplementary Material x; Table 3.1 DUNC16-C: Thin-section description

Context and Microstratigraphic Unit	Layer Thickness	Lower Boundary**	Structure					Void Type*				Fine Material		
			Textural Class	Microstructure	Course/Fine (100µm) Related Distribution	Course:Fine (100µm) Ratio	Porosity (%)	Channels and Vughs	Planar (Random)	Planar (Horizontal)	Compound Packing Voids	Nature of Fine Material (PPL)	Colour of Fine Material (OIL)	Birefringence Fabric (XPL)
1009.4	20 mm	Sharp												
1011	32 mm	Clear	Organic silt loam	Crumb with localised channels	Porphyric; unevenly distributed close to open porphyric	55:45	45	▪▪▪▪▪	+		▪▪▪▪▪▪▪▪▪▪	Orangish-brown; dark brown; dotted	Brownish-yellow; dark brown	Stipple-speckled
1013	33 mm	Bottom of slide	Sandy silt loam	Channels with localised subangular blocky structure	Porphyric; unevenly distributed close to open porphyric	65:35	30	▪▪▪▪▪▪▪▪▪▪	▪▪			Orangish-brown; dotted	Brownish-yellow	Stipple-speckled

Context and Microstratigraphic Unit	Organic Matter						Inclusions		Pedofeatures	
	Charred			*Uncharred*						
	Wood (Charcoal)	Plant	Amorphous Organic Matter	Plant	Fungal Sclerotia	Amorphous Organic Matter	Rubified Fine Mineral Material	Intrusive Aggregates	Fe/Mn	Excremental
1009.4										
1011	▪▪▪▪		▪▪▪			▪▪▪▪			▪▪▪▪▪▪	▪▪▪▪
1013	▪▪▪	+	▪▪	+	+	▪▪▪	▪		▪	▪▪▪

+ present in trace amounts; ▪ (<2%); ▪▪ (2-5%); ▪▪▪ (5-10%); ▪▪▪▪ (10-20%); ▪▪▪▪▪ (20-30%); ▪▪▪▪▪▪ (30-40%); ▪▪▪▪▪▪▪ (40-50%); ▪▪▪▪▪▪▪▪ (50-60%); ▪▪▪▪▪▪▪▪▪ (60-70%); ▪▪▪▪▪▪▪▪▪▪ (>70%)
* frequency class for voids refers to % total void space (following Bullock et al. 1985)

Supplementary Material x; Table 3.2 DUNC16-C: Thin-section interpretation



Context	Summary of key features	Interpretation
1009.4	Around 25% of what was captured in thin-section was disturbed by a large earthworm channel partially filled by round aggregrates. This horizon was not used for quantification; 1009.4 was quantified and examined using DUNC16-B.	n/a
1011	Organic silt loam with crumb structure and localised channels; small amount of subangular blocky towards bottom of layer. No anthropogenic inclusions other than charcoal and plant matter - 10% of layer occupied by large birch charcoal fragment (10 x 18 mm). Wood component also comprised hazel, including fragment with moderate ring curvature (at least 9 y/o). Limited number of fields of view available for quantification and assessment of microstructure. 30% of what was captured in thin-section was disturbed by a large, partially-infilled earthworm channel, and another 30% dominated by large pedofeature (Fe pseudomorph of plant matter - 10 x 35 mm).	Limited number of fields of view restrict interpretation but likely represents a bioturbated surface, forming an early floor or occupation deposit in the lower terrace structure (contemporary with the lower hearth). Fe pseudomorph formed through series of depositional and post-depositional events: 1) deposition of anthropogenic material 2) earthworm activity, partial ingestion of plant material and formation of crumb structure 3) Fe formation around plant material
1013	Sandy silt loam with channel microstructure and localised subangular blocky, lying directly above the subsoil or bedrock. Around 40% of the course fraction is composed of angular gravel-sized rock fragments (up to 1.5cm in size) No anthropogenic inclusions other than charcoal (max. 4 x 2 mm), which includes hazel fragments of variable ring width; one fragment with moderate ring curviture (at least 7 y/o).	First archaeological layer, lying directly above the subsoil or bedrock. Likely deposited during the primary construction of the structure in order to level the lower terrace hollow and create a suitable occupation surface.

SM2: Microrefuse, geochemical, magnetic, multi-element and statistical data

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Sheet 1: Grid coordinates and microrefuse data

Grid	POINT X	POINT Y	Charcoal (2-30mm)	Burnt Bone (2-15mm)	Unburnt bone	Shell	Waste Material	Fe objects
1	310866.1646	869140.4035	0	0	0	0	309	0
2	310866.4158	869140.8585	2	0	0	0	55	0
3	310865.9676	869141.103	0	0	0	0	45	0
4	310865.7231	869140.6412	0	0	0	0	769	0
5	310865.2817	869140.8857	13	0	0	0	32	0
6	310865.5262	869141.3407	0	0	2	0	36	2
7	310865.1051	869141.5648	0	0	0	0	812	0
8	310864.8471	869141.1166	0	0	1	0	44	0
9	310864.4192	869141.3543	0	0	0	0	20	0
10	310864.6569	869141.8161	0	0	0	0	708	0
11	310864.2155	869142.0402	0	0	0	0	13	0
12	310863.971	869141.592	4	0	2	0	728	0
13	310863.5296	869141.8365	0	0	0	0	542	0
14	310863.7741	869142.2847	0	0	0	0	366	0
15	310863.3327	869142.5224	3	0	0	0	37	0
16	310863.0882	869142.0741	2	0	0	0	26	0
17	310867.5364	869140.8382	0	0	0	0	90	0
18	310867.774	869141.2796	0	0	0	0	11	0
19	310867.3394	869141.5241	0	0	0	0	14	0
20	310867.0949	869141.0759	0	0	0	0	6	0
21	310866.6603	869141.3068	0	0	0	0	19	0
22	310866.9048	869141.755	74	0	0	1	0	0
23	310866.4634	869141.9927	51	0	0	0	0	0
24	310866.2189	869141.5512	20	0	0	0	0	0
25	310865.7775	869141.7821	0	0	0	0	0	0
26	310866.0219	869142.2439	0	0	0	0	11	0
27	310865.5873	869142.468	4	0	0	0	69	0
28	310865.3292	869142.0198	5	0	0	0	7	0
29	310864.9014	869142.2575	0	0	0	0	29	0
30	310865.1459	869142.7057	3	0	0	0	3	0
31	310864.7045	869142.9502	0	0	0	0	0	0

32	310864.46	869142.4952	0	0	0	0	6	0
33	310864.0186	869142.7397	0	0	0	0	22	1
34	310864.263	869143.1879	0	0	0	0	14	0
35	310863.8216	869143.4256	2	0	0	0	0	0
36	310863.5771	869142.9774	0	0	0	0	33	4
37	310868.0185	869141.7414	4	4	0	0	36	0
38	310868.263	869142.1896	0	0	0	0	6	0
39	310867.8284	869142.4273	15	5	7	0	0	0
40	310867.5839	869141.9655	8	6	0	0	10	0
41	310867.1425	869142.21	135	0	0	0	0	0
42	310867.3937	869142.665	12	0	0	0	2	0
43	310866.9523	869142.9027	23	0	0	0	5	0
44	310866.7146	869142.4477	0	0	0	0	0	0
45	310866.2596	869142.6786	16	2	0	0	0	0
46	310866.5177	869143.1336	0	0	0	0	13	0
47	310866.0695	869143.3712	0	0	0	0	0	0
48	310865.825	869142.923	0	0	0	0	20	0
49	310865.3972	869143.1675	0	0	0	0	0	0
50	310865.6348	869143.6225	0	0	0	0	0	0
51	310865.1866	869143.8466	0	1	0	0	5	0
52	310864.9422	869143.3984	27	0	6	0	1	0
53	310864.5075	869143.6361	16	0	0	0	3	0
54	310864.7656	869144.0911	13	1	0	0	12	0
55	310864.3174	869144.3424	16	0	0	0	0	0
56	310864.0661	869143.8738	27	0	0	0	0	0
57	310868.5075	869142.6446	0	0	0	0	0	0
58	310868.7384	869143.0928	8	0	0	3	31	0
59	310868.3241	869143.3237	6	0	0	1	9	0
60	310868.0796	869142.8755	3	0	0	0	1	0
61	310867.6382	869143.1132	7	0	0	0	0	0
62	310867.8827	869143.5614	1	0	0	0	0	0
63	310867.4413	869143.7991	0	0	0	0	10	0
64	310867.1968	869143.3441	0	0	0	0	14	0
65	310866.7486	869143.5886	0	0	0	0	4	0
66	310867.0067	869144.0368	0	0	0	0	14	0
67	310866.5584	869144.2813	0	0	0	0	10	3
68	310866.3207	869143.8263	0	0	0	0	27	0
69	310865.8793	869144.0639	0	0	0	0	0	0
70	310866.117	869144.5189	0	0	0	0	23	0

71	310865.6892	869144.7498	10	0	0	0	1	0
72	310865.4311	869144.2948	3	0	0	0	9	0
73	310864.9897	869144.5393	16	0	0	0	15	0
74	310865.241	869144.9943	0	0	0	0	0	0
75	310864.7995	869145.232	48	0	0	0	0	0
76	310864.5551	869144.777	18	0	0	0	0	0
77	310868.9829	869143.5478	0	0	0	0	14	0
78	310869.2138	869144.0164	0	0	0	0	3	0
79	310868.8199	869144.2269	5	0	0	0	0	0
80	310868.5754	869143.7719	0	0	0	0	20	0
81	310868.134	869144.0096	2	0	0	0	10	0
82	310868.3717	869144.4646	0	0	0	0	0	0
83	310867.9302	869144.7023	14	0	0	0	14	0
84	310867.6858	869144.2541	0	0	0	0	23	0
85	310867.2443	869144.4918	0	0	0	0	0	0
86	310867.4956	869144.9332	7	0	0	0	0	0
87	310867.0542	869145.1709	13	0	0	0	0	0
88	310866.8097	869144.7295	0	0	0	0	0	0
89	310866.3751	869144.9604	2	0	0	0	40	0
90	310866.6128	869145.4154	0	0	0	0	0	0
91	310866.1781	869145.6531	4	0	0	0	18	0
92	310865.9201	869145.1981	4	0	0	0	25	0
93	310865.4922	869145.4357	80	0	0	0	0	0
94	310865.7367	869145.8907	10	0	0	0	8	0
95	310865.2885	869146.1352	18	0	0	0	4	0
96	310865.044	869145.6802	26	0	0	0	0	0

Statistics	Charcoal	Burnt Bone	Unburnt bone	Shell	Waste Material	Fe objects
Mean	8	0	0	0	56	0
Median	0	0	0	0	9	0
SE	1.95	0.09	0.10	0.04	16.71	0.05
SD	19.13	0.93	0.98	0.37	163.74	0.50
Max	135	6	7	3	812	4
Min	0	0	0	0	0	0

Sheet 2: Grid coordinates, geochemical and magnetic data

Grid	POINT X	POINT Y	pH	EC	LOI	Mag sus
1	310866.1646	869140.4035	7.02	319	6.255850987	87
2	310866.4158	869140.8585	7.12	153	1.609302602	16.4
3	310865.9676	869141.103	7.11	200	1.616314645	18.8
4	310865.7231	869140.6412	6.97	384	14.47470899	257.5
5	310865.2817	869140.8857	6.81	353	2.887660191	65.6
6	310865.5262	869141.3407	7.11	195	1.275486833	25
7	310865.1051	869141.5648	7.18	308	11.44603772	117
8	310864.8471	869141.1166	7.31	140	3.651197716	33.5
9	310864.4192	869141.3543	7.2	149	1.101374095	20.5
10	310864.6569	869141.8161	6.87	711	14.23158769	248.9
11	310864.2155	869142.0402	7.29	116	1.510233946	36.2
12	310863.971	869141.592	6.85	411	11.57598647	156.7
13	310863.5296	869141.8365	7.1	324	9.568920478	384.6
14	310863.7741	869142.2847	6.98	370	4.423361755	292.6
15	310863.3327	869142.5224	6.68	448	2.94102769	69.7
16	310863.0882	869142.0741	7.24	250	2.402873113	35.9
17	310867.5364	869140.8382	7.2	134	1.350146478	16.7
18	310867.774	869141.2796	7.21	181	1.484613018	36.7
19	310867.3394	869141.5241	7.08	190	2.158948386	57.4
20	310867.0949	869141.0759	7.19	203	1.488619711	30
21	310866.6603	869141.3068	7.41	114	1.270460376	34
22	310866.9048	869141.755	6.82	233	5.215696312	182.9
23	310866.4634	869141.9927	6.96	230	3.084513733	83.6
24	310866.2189	869141.5512	7.12	174	2.068837209	21.7
25	310865.7775	869141.7821	7.04	251	4.73368256	94.9
26	310866.0219	869142.2439	7.11	239	0.87428732	11.1
27	310865.5873	869142.468	7.21	264	2.518908378	41.5
28	310865.3292	869142.0198	6.82	100	0.76732918	6.8
29	310864.9014	869142.2575	7.32	126	1.219499161	19
30	310865.1459	869142.7057	7.38	83	0.962901762	11.4
31	310864.7045	869142.9502	7.39	142	0.977303172	7.8
32	310864.46	869142.4952	7.08	102	0.951921471	14.4
33	310864.0186	869142.7397	7.06	232	1.56741357	29.4
34	310864.263	869143.1879	7.41	78	0.735694553	7.7
35	310863.8216	869143.4256	7.43	86	0.930720784	8.5

36	310863.5771	869142.9774	7.33	73	1.242266048	18.1
37	310868.0185	869141.7414	6.95	146	1.664748074	49
38	310868.263	869142.1896	7.28	119	1.041496212	7.2
39	310867.8284	869142.4273	7.09	200	2.06209389	41.6
40	310867.5839	869141.9655	7.22	203	2.646092669	57.2
41	310867.1425	869142.21	6.9	387	5.025052947	149.5
42	310867.3937	869142.665	7.15	215	2.705862198	84.5
43	310866.9523	869142.9027	7.02	214	2.11682794	58.8
44	310866.7146	869142.4477	7.15	92	0.993873924	10.4
45	310866.2596	869142.6786	7.28	127	1.28750957	34
46	310866.5177	869143.1336	7.32	76	0.677728441	5.3
47	310866.0695	869143.3712	7.16	102	0.702149705	8.2
48	310865.825	869142.923	7.12	176	1.378018164	17.9
49	310865.3972	869143.1675	7.11	108	0.86188377	12
50	310865.6348	869143.6225	7.26	119	0.544265594	3.6
51	310865.1866	869143.8466	6.91	185	1.069341269	10.8
52	310864.9422	869143.3984	7.14	227	1.627654776	25.3
53	310864.5075	869143.6361	7.24	170	1.401454494	27.7
54	310864.7656	869144.0911	7.23	205	1.334947957	23
55	310864.3174	869144.3424	7.2	107	1.865649921	39.3
56	310864.0661	869143.8738	6.96	250	1.913228808	44.3
57	310868.5075	869142.6446	7.19	111	1.330882947	17
58	310868.7384	869143.0928	6.88	238	2.304095716	54.2
59	310868.3241	869143.3237	7.02	115	0.897992722	8.4
60	310868.0796	869142.8755	6.94	178	1.068057625	15
61	310867.6382	869143.1132	6.86	356	1.92763375	55.1
62	310867.8827	869143.5614	7.01	154	1.111879818	26.3
63	310867.4413	869143.7991	6.93	182	1.225214561	33.4
64	310867.1968	869143.3441	7.28	95	1.12210824	20.2
65	310866.7486	869143.5886	7.17	106	0.888161261	60.9
66	310867.0067	869144.0368	7.24	120	0.956897282	13.4
67	310866.5584	869144.2813	7.09	114	1.070757921	19.2
68	310866.3207	869143.8263	7.09	206	1.500181158	34.9
69	310865.8793	869144.0639	7.14	78	0.609211274	6.4
70	310866.117	869144.5189	7.09	113	1.193380559	19.6
71	310865.6892	869144.7498	6.91	202	1.850619514	21.6
72	310865.4311	869144.2948	7.08	106	1.006086459	11.7
73	310864.9897	869144.5393	7.19	201	2.014648257	34.2
74	310865.241	869144.9943	7.36	88	0.968285016	10.9

75	310864.7995	869145.232	7.3	156	2.528631587	61.7
76	310864.5551	869144.777	7.06	369	2.351114341	63.8
77	310868.9829	869143.5478	7.23	115	0.826250451	17.5
78	310869.2138	869144.0164	6.85	80	0.478554408	2.7
79	310868.8199	869144.2269	6.94	125	0.590891947	4.9
80	310868.5754	869143.7719	7.11	80	0.507143902	5.5
81	310868.134	869144.0096	7.1	206	1.327642966	29.4
82	310868.3717	869144.4646	7.26	60	0.535875564	5.3
83	310867.9302	869144.7023	7.29	112	1.060766783	10
84	310867.6858	869144.2541	7.27	69	0.643335846	8.2
85	310867.2443	869144.4918	7.04	137	0.679670975	11.7
86	310867.4956	869144.9332	7.06	183	0.992792986	13.4
87	310867.0542	869145.1709	7.25	96	1.112206246	33.1
88	310866.8097	869144.7295	7.09	91	0.725833392	8.4
89	310866.3751	869144.9604	7.11	118	0.956172983	29.2
90	310866.6128	869145.4154	7.13	116	0.939663699	8.9
91	310866.1781	869145.6531	7.04	315	2.703892901	40
92	310865.9201	869145.1981	7.05	246	0.998053274	21.9
93	310865.4922	869145.4357	7	381	3.316520283	62.5
94	310865.7367	869145.8907	6.95	240	1.526528018	18.7
95	310865.2885	869146.1352	7.09	182	2.178542487	24.1
96	310865.044	869145.6802	7.2	231	2.789920538	80.4

Statistics	**pH**	**EC**	**LOI**	**Mag sus**
Mean	7.1	187.1	2.2	45.1
Median	7.1	172.0	1.3	24.6
SE	0.02	10.74	0.27	6.43
SD	0.16	105.24	2.64	62.99
Max	7.4	711	14.5	384.6
Min	6.7	60	0.5	2.7

Sheet 3: Multi-element data

Grid	Al	Ba	Ca	Cr[1]	Fe	K	P	Rb	S[2]	Si	Sr	Ti	Zr	Cl*[3]	Cu*[4]	Ni*[5]	Pb*[6]	V*[7]	Zn*[8]
1	7.7962	0.0400	3.3044	0.0090	1.9348	0.7000	0.2556	0.0038	0.2534	23.5834	0.0236	0.3306	0.0080	0.0150	0.0070	0.0046	0.0132	0.0132	0.0092
2	2.4334	0.0380	0.3740	0.0019	0.4130	0.9396	0.1150	0.0034	0.0304	42.0074	0.0092	0.0592	0.0060	0.0020	0.0010	0.0020	0.0040	0.0018	0.0030
3	2.8790	0.0364	0.5024	0.0048	0.4876	1.1910	0.1300	0.0038	0.0526	41.8384	0.0100	0.0554	0.0056	0.0020	0.0010	0.0020	0.0026	0.0015	0.0016
4	6.1922	0.0462	3.4980	0.0122	2.8388	0.5152	0.2116	0.0038	0.4402	19.6568	0.0250	0.2052	0.0076	0.0534	0.0038	0.0032	0.0058	0.0114	0.0058
5	3.6700	0.0344	0.9174	0.0043	0.7498	1.1708	0.1622	0.0040	0.0936	38.4772	0.0126	0.0992	0.0052	0.0052	0.0010	0.0020	0.0076	0.0020	0.0018
6	2.7304	0.0366	0.6556	0.0021	0.4242	1.0788	0.1496	0.0036	0.0562	42.0440	0.0100	0.0656	0.0064	0.0020	0.0010	0.0020	0.0038	0.0015	0.0018
7	5.3922	0.0386	1.7930	0.0110	1.8804	0.6748	0.2282	0.0034	0.3728	27.0598	0.0184	0.1638	0.0070	0.0294	0.0020	0.0020	0.0070	0.0086	0.0054
8	3.6370	0.0292	0.8286	0.0036	0.6584	1.1450	0.1600	0.0036	0.0858	38.0912	0.0110	0.2092	0.0072	0.0030	0.0010	0.0020	0.0064	0.0026	0.0038
9	2.8142	0.0308	0.4512	0.0032	0.2940	1.2120	0.1090	0.0040	0.0394	42.0658	0.0108	0.0398	0.0050	0.0020	0.0010	0.0020	0.0020	0.0015	0.0014
10	12.2530	0.0450	2.5336	0.0166	4.2416	0.4306	0.3724	0.0032	0.2540	20.3532	0.0960	0.4284	0.0122	0.0292	0.0140	0.0148	0.0188	0.0202	0.0088
11	2.5532	0.0370	0.4394	0.0031	0.6496	1.0520	0.1186	0.0038	0.0346	41.7608	0.0112	0.0444	0.0044	0.0020	0.0010	0.0020	0.0028	0.0015	0.0012
12	6.3980	0.0474	2.2586	0.0096	2.6154	0.5878	0.2262	0.0036	0.5618	21.6606	0.0258	0.2196	0.0088	0.0406	0.0048	0.0034	0.0282	0.0130	0.0092
13	8.5590	0.0384	2.6970	0.0124	2.8586	0.6080	0.3478	0.0038	0.2550	21.9048	0.0442	0.3874	0.0090	0.0366	0.0124	0.0082	0.0278	0.0208	0.0150
14	5.6510	0.0426	1.0126	0.0072	2.3604	0.9622	0.2468	0.0036	0.1292	36.8690	0.0198	0.1672	0.0062	0.0056	0.0010	0.0020	0.0110	0.0063	0.0166
15	3.3574	0.0384	0.6050	0.0044	0.4840	1.2172	0.1664	0.0038	0.1072	39.0446	0.0112	0.0962	0.0080	0.0092	0.0010	0.0020	0.0048	0.0022	0.0040
16	2.9836	0.0374	0.6350	0.0030	0.3682	1.1012	0.1300	0.0040	0.1056	38.7118	0.0112	0.0622	0.0056	0.0026	0.0010	0.0020	0.0042	0.0015	0.0042
17	3.4276	0.0292	0.7642	0.0025	0.4326	1.0852	0.1614	0.0036	0.0866	41.4538	0.0122	0.0942	0.0050	0.0020	0.0010	0.0020	0.0094	0.0015	0.0056
18	2.4792	0.0338	0.5088	0.0026	0.3716	1.1302	0.0902	0.0038	0.0390	38.7968	0.0108	0.0440	0.0046	0.0020	0.0010	0.0020	0.0020	0.0015	0.0010
19	2.3624	0.0286	0.5350	0.0025	0.3030	1.1332	0.1208	0.0038	0.0502	38.9846	0.0106	0.0388	0.0062	0.0020	0.0010	0.0020	0.0014	0.0015	0.0010
20	2.1720	0.0306	0.4998	0.0056	0.4014	1.0482	0.0668	0.0038	0.0228	40.3948	0.0106	0.0426	0.0052	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
21	2.2026	0.0290	0.4724	0.0048	0.3302	1.0826	0.0778	0.0040	0.0520	40.2154	0.0104	0.0470	0.0050	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
22	2.8864	0.0376	1.8328	0.0054	0.8616	1.1750	0.2148	0.0042	0.1152	33.7204	0.0158	0.1270	0.0088	0.0102	0.0010	0.0020	0.0028	0.0015	0.0042
23	2.6474	0.0346	1.1188	0.0042	0.4870	1.1642	0.1724	0.0040	0.0734	37.4044	0.0140	0.0624	0.0056	0.0026	0.0010	0.0020	0.0012	0.0015	0.0018
24	2.4746	0.0326	0.4312	0.0038	0.3274	1.0286	0.0940	0.0034	0.0360	41.7402	0.0102	0.0442	0.0076	0.0020	0.0010	0.0020	0.0030	0.0015	0.0020
25	2.8078	0.0346	1.4664	0.0066	0.6962	1.1054	0.2204	0.0040	0.1260	35.5714	0.0134	0.0784	0.0062	0.0154	0.0010	0.0020	0.0030	0.0020	0.0046

[1] Non-detect substituted with LOD/2 = 0.0015
[2] Non-detect substituted with LOD/2 = 0.0030
[3] Non-detect substituted with LOD/2 = 0.0020
[4] Non-detect substituted with LOD/2 = 0.0010
[5] Non-detect substituted with LOD/2 = 0.0020
[6] Non-detect substituted with LOD/2 = 0.0010
[7] Non-detect substituted with LOD/2 = 0.0015
[8] Non-detect substituted with LOD/2 = 0.0010
* Elements with number of non-detect values greater than 25%

26	2.5348	0.0312	0.3512	0.0040	0.2458	1.2082	0.0860	0.0040	0.0166	41.5538	0.0110	0.0318	0.0054	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
27	2.9606	0.0438	0.6926	0.0048	0.9372	1.2332	0.1140	0.0042	0.0972	39.6532	0.0140	0.0724	0.0054	0.0076	0.0010	0.0020	0.0052	0.0015	0.0186
28	2.3934	0.0348	0.2800	0.0015	0.2326	0.9802	0.0716	0.0034	0.0056	42.4392	0.0106	0.0280	0.0036	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
29	2.5152	0.0336	0.3576	0.0035	0.2728	1.2820	0.0820	0.0042	0.0162	43.1150	0.0116	0.0386	0.0054	0.0020	0.0010	0.0020	0.0012	0.0015	0.0012
30	2.6952	0.0318	0.3456	0.0020	0.3048	1.3508	0.0884	0.0044	0.0164	42.6382	0.0128	0.0460	0.0048	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
31	2.6430	0.0290	0.3402	0.0040	0.2742	1.1660	0.0942	0.0040	0.0126	45.9892	0.0122	0.0402	0.0058	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
32	2.3370	0.0312	0.3404	0.0026	0.2946	1.1204	0.0728	0.0034	0.0162	43.2466	0.0106	0.0546	0.0048	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
33	2.4008	0.0266	0.4994	0.0025	0.3532	1.1422	0.1012	0.0042	0.0406	43.1136	0.0106	0.0512	0.0066	0.0020	0.0010	0.0020	0.0016	0.0015	0.0012
34	2.0948	0.0314	0.2832	0.0020	0.2376	1.0504	0.0728	0.0040	0.0052	43.5050	0.0112	0.0264	0.0052	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
35	2.4068	0.0268	0.3330	0.0026	0.2652	1.1390	0.0980	0.0044	0.0136	42.8170	0.0118	0.0346	0.0046	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
36	2.3056	0.0282	0.3214	0.0033	0.2936	1.0900	0.0842	0.0036	0.0116	43.2844	0.0114	0.0372	0.0044	0.0020	0.0010	0.0020	0.0016	0.0015	0.0010
37	2.4166	0.0298	0.7286	0.0018	0.3194	1.0404	0.1650	0.0038	0.0470	40.7146	0.0114	0.0474	0.0046	0.0020	0.0010	0.0020	0.0030	0.0015	0.0048
38	2.5034	0.0292	0.4020	0.0030	0.2632	1.3396	0.0654	0.0046	0.0170	41.7162	0.0112	0.0430	0.0046	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
39	2.5940	0.0324	1.4084	0.0034	0.5482	1.2024	0.3924	0.0040	0.0372	40.2088	0.0146	0.0510	0.0064	0.0020	0.0010	0.0020	0.0012	0.0015	0.0024
40	2.5656	0.0340	0.8362	0.0032	0.4424	1.1976	0.1246	0.0046	0.1200	39.4226	0.0124	0.0554	0.0050	0.0020	0.0010	0.0020	0.0028	0.0015	0.0072
41	2.8554	0.0344	1.4648	0.0054	0.7192	1.1256	0.1970	0.0038	0.1022	37.8004	0.0146	0.0956	0.0118	0.0078	0.0010	0.0020	0.0026	0.0015	0.0040
42	2.6146	0.0306	1.4404	0.0056	0.5930	1.1214	0.2022	0.0038	0.0556	38.0586	0.0136	0.0856	0.0070	0.0020	0.0010	0.0020	0.0040	0.0015	0.0026
43	2.3220	0.0300	0.6158	0.0040	0.5770	1.0800	0.1154	0.0040	0.0602	40.1354	0.0120	0.0462	0.0080	0.0020	0.0010	0.0020	0.0232	0.0015	0.0020
44	2.6264	0.0322	0.3534	0.0034	0.2690	1.1086	0.0690	0.0038	0.0094	43.4080	0.0110	0.0372	0.0048	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
45	2.4014	0.0334	0.4406	0.0034	0.2802	1.0714	0.0752	0.0038	0.0180	42.1262	0.0122	0.0376	0.0042	0.0020	0.0010	0.0020	0.0012	0.0015	0.0010
46	1.9214	0.0244	0.2502	0.0015	0.1712	0.9922	0.0430	0.0034	0.0030	42.7274	0.0100	0.0262	0.0050	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
47	2.5540	0.0348	0.3326	0.0018	0.2330	1.2622	0.0816	0.0040	0.0048	43.4866	0.0124	0.0366	0.0046	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
48	2.5596	0.0336	0.4078	0.0023	0.2562	1.2610	0.0968	0.0050	0.0300	41.8548	0.0118	0.0346	0.0044	0.0020	0.0010	0.0020	0.0016	0.0015	0.0010
49	2.5638	0.0324	0.4016	0.0019	0.2532	1.1754	0.0708	0.0040	0.0030	44.7960	0.0118	0.0396	0.0046	0.0020	0.0010	0.0020	0.0010	0.0018	0.0010
50	2.7220	0.0242	0.3390	0.0024	0.2072	1.4744	0.0740	0.0052	0.0030	43.2686	0.0128	0.0302	0.0052	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
51	2.6260	0.0366	0.3810	0.0021	0.2750	1.1574	0.1216	0.0038	0.0204	43.1426	0.0114	0.0388	0.0044	0.0020	0.0010	0.0020	0.0010	0.0015	0.0012
52	2.2918	0.0260	0.5638	0.0034	0.2856	1.1440	0.1168	0.0042	0.0302	41.6344	0.0122	0.0456	0.0058	0.0020	0.0010	0.0020	0.0010	0.0015	0.0012
53	2.4554	0.0338	0.3938	0.0044	0.3150	1.1764	0.0846	0.0046	0.0104	42.5262	0.0114	0.0424	0.0046	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
54	2.2926	0.0242	0.3434	0.0052	0.2480	1.1430	0.0984	0.0038	0.0124	43.3866	0.0114	0.0414	0.0046	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
55	2.4904	0.0410	0.4456	0.0037	0.3164	1.2228	0.1954	0.0038	0.0332	42.5048	0.0118	0.0492	0.0048	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
56	2.1418	0.0308	0.5238	0.0058	0.3496	1.0814	0.1046	0.0040	0.0288	38.5308	0.0118	0.0618	0.0060	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
57	2.0060	0.0226	0.4140	0.0015	0.5176	1.1278	0.0552	0.0040	0.0128	40.5060	0.0120	0.0298	0.0056	0.0020	0.0010	0.0020	0.0014	0.0015	0.0012
58	2.4828	0.0318	0.7532	0.0054	0.3982	1.1578	0.1108	0.0038	0.0518	38.5312	0.0118	0.0556	0.0074	0.0020	0.0010	0.0020	0.0046	0.0015	0.0042
59	1.9736	0.0282	0.4008	0.0035	0.2496	0.9628	0.0780	0.0034	0.0118	41.2138	0.0102	0.0338	0.0050	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
60	2.2394	0.0332	0.4200	0.0023	0.3124	1.1432	0.0804	0.0038	0.0158	41.3280	0.0108	0.0558	0.0044	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
61	2.1072	0.0352	0.9798	0.0036	0.3238	1.1100	0.2634	0.0040	0.0404	39.4496	0.0120	0.0420	0.0052	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
62	2.1518	0.0208	0.4210	0.0022	0.2688	0.9940	0.0928	0.0032	0.0114	42.0072	0.0100	0.0394	0.0046	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
63	2.7660	0.0368	0.4904	0.0096	0.3308	1.2782	0.0942	0.0042	0.0124	43.0788	0.0116	0.0420	0.0060	0.0020	0.0010	0.0020	0.0010	0.0018	0.0016
64	2.4140	0.0352	0.3810	0.0048	0.2724	1.1234	0.1008	0.0036	0.0184	42.5476	0.0110	0.0336	0.0050	0.0020	0.0010	0.0020	0.0026	0.0015	0.0010
65	2.6848	0.0302	0.3736	0.0041	0.3284	1.2756	0.1012	0.0040	0.0160	42.3522	0.0108	0.0468	0.0046	0.0020	0.0010	0.0020	0.0020	0.0015	0.0010

66	2.6144	0.0386	0.3922	0.0030	0.3054	1.2564	0.0892	0.0042	0.0072	43.2260	0.0116	0.0524	0.0052	0.0020	0.0010	0.0020	0.0016	0.0015	0.0028
67	2.7790	0.0360	0.3670	0.0031	0.2906	1.2402	0.1122	0.0040	0.0156	45.8784	0.0118	0.0462	0.0074	0.0020	0.0010	0.0020	0.0016	0.0018	0.0038
68	2.6870	0.0322	0.5286	0.0035	0.3024	1.0856	0.1396	0.0042	0.0526	42.1152	0.0118	0.0644	0.0056	0.0020	0.0010	0.0020	0.0026	0.0015	0.0060
69	2.8110	0.0354	0.3662	0.0033	0.2492	1.2678	0.0862	0.0042	0.0048	43.5410	0.0120	0.0410	0.0054	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
70	2.6818	0.0388	0.3706	0.0015	0.2448	1.2226	0.1076	0.0036	0.0188	43.9188	0.0110	0.0354	0.0058	0.0020	0.0010	0.0020	0.0016	0.0015	0.0030
71	2.9190	0.0382	0.5776	0.0048	0.3592	1.3118	0.1558	0.0038	0.0398	41.7312	0.0124	0.0550	0.0054	0.0020	0.0010	0.0020	0.0010	0.0015	0.0012
72	2.4296	0.0214	0.3040	0.0044	0.2538	1.1068	0.0954	0.0038	0.0050	45.9928	0.0106	0.0368	0.0046	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
73	2.2824	0.0364	0.5394	0.0056	0.3252	1.0716	0.1478	0.0042	0.0330	41.0764	0.0108	0.0402	0.0046	0.0020	0.0010	0.0020	0.0024	0.0015	0.0040
74	2.7716	0.0342	0.3814	0.0047	0.2940	1.3140	0.1260	0.0040	0.0212	41.9518	0.0114	0.0454	0.0042	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
75	2.8146	0.0414	0.6882	0.0072	0.5832	1.1930	0.1574	0.0044	0.0400	40.2214	0.0130	0.0526	0.0052	0.0020	0.0010	0.0020	0.0010	0.0020	0.0012
76	2.5760	0.0374	0.8522	0.0046	0.4278	1.1490	0.1944	0.0038	0.0668	41.2136	0.0118	0.0684	0.0052	0.0092	0.0010	0.0020	0.0018	0.0015	0.0032
77	2.7476	0.0384	0.4194	0.0039	0.3298	1.2302	0.0882	0.0040	0.0044	44.2742	0.0116	0.0430	0.0056	0.0020	0.0010	0.0020	0.0010	0.0015	0.0012
78	2.3922	0.0344	0.3018	0.0029	0.2494	1.0908	0.0660	0.0034	0.0030	43.9858	0.0114	0.0322	0.0050	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
79	2.5476	0.0190	0.3528	0.0024	0.2852	1.1848	0.0674	0.0040	0.0052	47.6000	0.0110	0.0390	0.0048	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
80	2.2950	0.0352	0.2866	0.0032	0.2022	1.1648	0.0674	0.0036	0.0030	42.6292	0.0110	0.0298	0.0046	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
81	2.3966	0.0348	0.4500	0.0027	0.2402	1.1384	0.0870	0.0040	0.0232	43.2078	0.0114	0.0588	0.0048	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
82	2.3552	0.0252	0.3194	0.0024	0.2526	1.2258	0.0658	0.0038	0.0030	46.5056	0.0112	0.0368	0.0044	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
83	2.4320	0.0362	0.5204	0.0028	0.2538	1.1254	0.1444	0.0036	0.0096	43.8194	0.0106	0.0394	0.0052	0.0020	0.0010	0.0020	0.0012	0.0015	0.0010
84	2.3872	0.0366	0.2936	0.0025	0.2604	1.1194	0.0676	0.0040	0.0030	44.8580	0.0118	0.0446	0.0046	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
85	2.5930	0.0374	0.3926	0.0026	0.2884	1.1942	0.0730	0.0038	0.0040	44.9148	0.0116	0.0412	0.0054	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
86	2.5064	0.0380	0.3736	0.0038	0.3662	1.1588	0.0880	0.0036	0.0062	45.1448	0.0118	0.0430	0.0050	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
87	2.5884	0.0368	0.4768	0.0040	0.3330	1.2862	0.1076	0.0044	0.0152	44.0898	0.0122	0.0586	0.0056	0.0020	0.0010	0.0020	0.0012	0.0015	0.0010
88	2.7744	0.0352	0.4062	0.0025	0.2260	1.2280	0.0824	0.0042	0.0090	44.0752	0.0122	0.0344	0.0048	0.0020	0.0010	0.0020	0.0010	0.0015	0.0020
89	2.5650	0.0354	0.3424	0.0056	0.4176	1.0446	0.0924	0.0034	0.0144	45.7654	0.0110	0.0374	0.0046	0.0020	0.0010	0.0020	0.0018	0.0015	0.0052
90	2.6576	0.0370	0.3880	0.0028	0.2952	1.2674	0.1136	0.0040	0.0206	43.9492	0.0114	0.0350	0.0048	0.0020	0.0010	0.0020	0.0016	0.0015	0.0014
91	2.8400	0.0328	0.4730	0.0054	0.4328	1.0722	0.1530	0.0032	0.0566	43.8956	0.0104	0.0888	0.0056	0.0020	0.0010	0.0020	0.0068	0.0015	0.0056
92	2.8078	0.0364	0.4040	0.0030	0.2908	1.2348	0.1078	0.0034	0.0164	44.1756	0.0114	0.0382	0.0044	0.0020	0.0010	0.0020	0.0012	0.0020	0.0022
93	2.6394	0.0366	1.0952	0.0028	0.3632	1.1192	0.1790	0.0036	0.0612	40.7518	0.0134	0.0574	0.0072	0.0020	0.0010	0.0020	0.0012	0.0015	0.0014
94	2.9382	0.0372	0.4728	0.0021	0.2940	1.3102	0.1358	0.0036	0.0446	44.9246	0.0106	0.0468	0.0052	0.0020	0.0010	0.0020	0.0078	0.0015	0.0016
95	2.7302	0.0368	0.5624	0.0031	0.3282	1.1360	0.1714	0.0044	0.0562	42.1900	0.0126	0.0502	0.0044	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010
96	2.6250	0.0366	0.8412	0.0044	0.3626	1.1212	0.1978	0.0038	0.0488	40.5618	0.0134	0.0664	0.0050	0.0020	0.0010	0.0020	0.0010	0.0015	0.0020

Statistics	Al	Ba	Ca	Cr	Fe	K	P	Rb	S	Si	Sr	Ti	Zr	Cl	Cu	Ni	Pb	V	Zn
Mean	2.9331	0.0338	0.6826	0.0041	0.5293	1.1200	0.1287	0.0039	0.0549	40.7231	0.0134	0.0673	0.0056	0.0046	0.0014	0.0023	0.0032	0.0024	0.0027
Median	2.5822	0.0345	0.4478	0.0034	0.3216	1.1406	0.1077	0.0038	0.0260	42.0257	0.0116	0.0455	0.0052	0.0020	0.0010	0.0020	0.0012	0.0015	0.0012
SE	0.1474	0.0005	0.0628	0.0003	0.0666	0.0171	0.0068	0.0000	0.0091	0.5478	0.0010	0.0070	0.0001	0.0009	0.0002	0.0002	0.0005	0.0003	0.0003
SD	1.4439	0.0053	0.6149	0.0025	0.6528	0.1678	0.0664	0.0004	0.0892	5.3674	0.0095	0.0681	0.0015	0.0085	0.0019	0.0015	0.0051	0.0034	0.0032
Max	12.2530	0.0474	3.4980	0.0166	4.2416	1.4744	0.3924	0.0052	0.5618	47.6000	0.0960	0.4284	0.0122	0.0534	0.0140	0.0148	0.0282	0.0208	0.0186
Min	1.9214	0.0190	0.2502	0.0015	0.1712	0.4306	0.0430	0.0032	0.0030	19.6568	0.0092	0.0262	0.0036	0.0020	0.0010	0.0020	0.0010	0.0015	0.0010

Sheet 4: Correlations

		pH	EC	LOI	MagSus	Al	Ba	Ca	Cr	Fe	K	P	Rb	S	Si	Sr	Ti	Zr
pH	Pearson Correlation	1	-.565**	-.312**	-.331**	-.256*	-.258*	-.336**	-.237*	-.278**	.244*	-.345**	.296**	-.294**	.299**	-.216*	-.260*	-.395**
	Sig. (2-tailed)		0.000	0.002	0.001	0.012	0.011	0.001	0.020	0.006	0.016	0.001	0.003	0.004	0.003	0.034	0.010	0.000
EC	Pearson Correlation	-.565**	1	.743**	.686**	.677**	.455**	.681**	.674**	.712**	-.542**	.712**	-0.199	.653**	-.699**	.638**	.676**	.702**
	Sig. (2-tailed)	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.052	0.000	0.000	0.000	0.000	0.000
LOI	Pearson Correlation	-.312**	.743**	1	.823**	.843**	.506**	.896**	.850**	.924**	-.804**	.706**	-.214*	.927**	-.937**	.726**	.844**	.711**
	Sig. (2-tailed)	0.002	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.036	0.000	0.000	0.000	0.000	0.000
MagSus	Pearson Correlation	-.331**	.686**	.823**	1	.763**	.451**	.805**	.768**	.860**	-.658**	.734**	-0.147	.716**	-.815**	.658**	.802**	.670**
	Sig. (2-tailed)	0.001	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.153	0.000	0.000	0.000	0.000	0.000
Al	Pearson Correlation	-.256*	.677**	.843**	.763**	1	.488**	.791**	.817**	.948**	-.734**	.675**	-.213*	.742**	-.830**	.894**	.951**	.647**
	Sig. (2-tailed)	0.012	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.037	0.000	0.000	0.000	0.000	0.000
Ba	Pearson Correlation	-.258*	.455**	.506**	.451**	.488**	1	.462**	.477**	.511**	-.311**	.466**	-0.110	.509**	-.466**	.364**	.431**	.330**
	Sig. (2-tailed)	0.011	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.002	0.000	0.285	0.000	0.000	0.000	0.000	0.001
Ca	Pearson Correlation	-.336**	.681**	.896**	.805**	.791**	.462**	1	.772**	.841**	-.728**	.779**	-0.132	.852**	-.929**	.620**	.846**	.694**
	Sig. (2-tailed)	0.001	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.199	0.000	0.000	0.000	0.000	0.000
Cr	Pearson Correlation	-.237*	.674**	.850**	.768**	.817**	.477**	.772**	1	.856**	-.689**	.638**	-0.161	.734**	-.811**	.736**	.797**	.630**
	Sig. (2-tailed)	0.020	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.118	0.000	0.000	0.000	0.000	0.000
Fe	Pearson Correlation	-.278**	.712**	.924**	.860**	.948**	.511**	.841**	.856**	1	-.808**	.695**	-.231*	.835**	-.894**	.843**	.914**	.672**
	Sig. (2-tailed)	0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.023	0.000	0.000	0.000	0.000	0.000
K	Pearson Correlation	.244*	-.542**	-.804**	-.658**	-.734**	-.311**	-.728**	-.689**	-.808**	1	-.511**	.503**	-.756**	.799**	-.638**	-.745**	-.512**
	Sig. (2-tailed)	0.016	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000
P	Pearson Correlation	-.345**	.712**	.706**	.734**	.675**	.466**	.779**	.638**	.695**	-.511**	1	-0.153	.615**	-.703**	.601**	.718**	.616**
	Sig. (2-tailed)	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.137	0.000	0.000	0.000	0.000	0.000
Rb	Pearson Correlation	.296**	-0.199	-.214*	-0.147	-.213*	-0.110	-0.132	-0.161	-.231*	.503**	-0.153	1	-0.173	0.152	-0.181	-.229*	-0.184
	Sig. (2-tailed)	0.003	0.052	0.036	0.153	0.037	0.285	0.199	0.118	0.023	0.000	0.137		0.093	0.138	0.077	0.025	0.072

S	Pearson Correlation	-.294**	.653**	.927**	.716**	.742**	.509**	.852**	.734**	.835**	-.756**	.615**	-0.173	1	-.904**	.521**	.752**	.598**
	Sig. (2-tailed)	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.093		0.000	0.000	0.000	0.000
Si	Pearson Correlation	.299**	-.699**	-.937**	-.815**	-.830**	-.466**	-.929**	-.811**	-.894**	.799**	-.703**	0.152	-.904**	1	-.683**	-.868**	-.675**
	Sig. (2-tailed)	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.138	0.000		0.000	0.000	0.000
Sr	Pearson Correlation	-.216*	.638**	.726**	.658**	.894**	.364**	.620**	.736**	.843**	-.638**	.601**	-0.181	.521**	-.683**	1	.816**	.621**
	Sig. (2-tailed)	0.034	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.077	0.000	0.000		0.000	0.000
Ti	Pearson Correlation	-.260*	.676**	.844**	.802**	.951**	.431**	.846**	.797**	.914**	-.745**	.718**	-.229*	.752**	-.868**	.816**	1	.703**
	Sig. (2-tailed)	0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.025	0.000	0.000	0.000		0.000
Zr	Pearson Correlation	-.395**	.702**	.711**	.670**	.647**	.330**	.694**	.630**	.672**	-.512**	.616**	-0.184	.598**	-.675**	.621**	.703**	1
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.072	0.000	0.000	0.000	0.000	

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

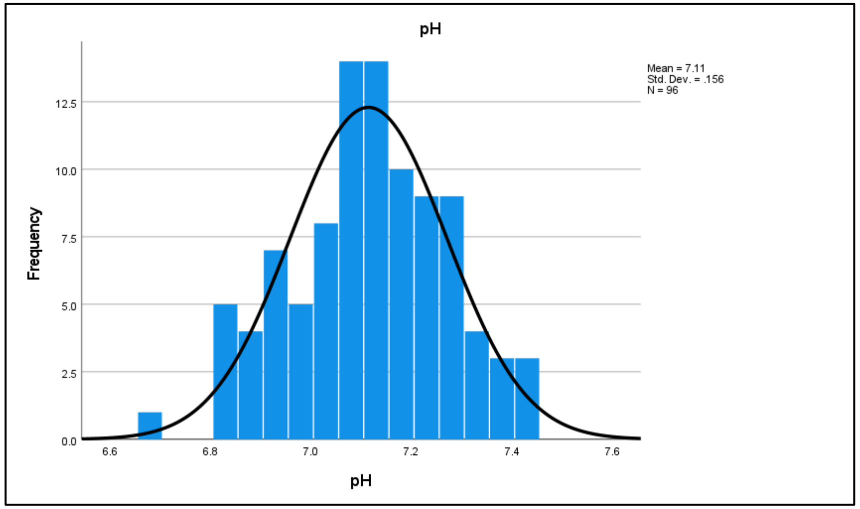
Sheet 5: Grid coordinates and PCA results

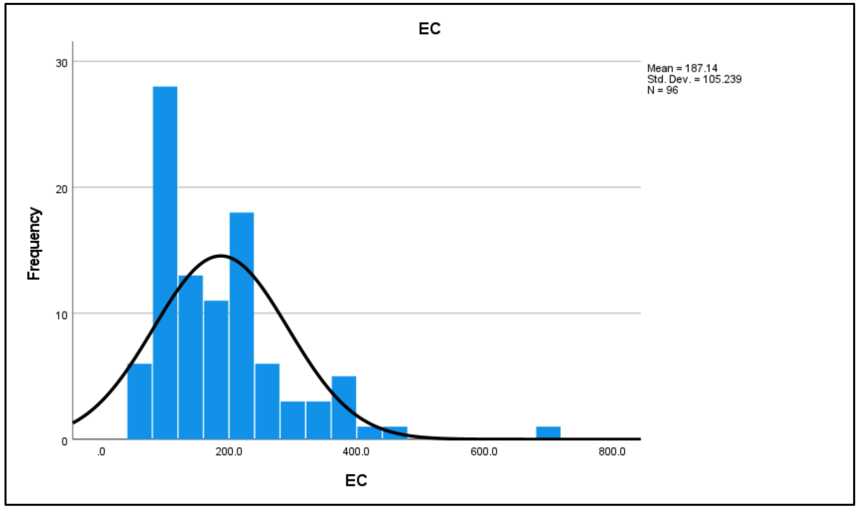
Grid	POINT X	POINT Y	PC1	PC2	PC3
1	310866.1646	869140.4035	8.629	0.881	-0.600
2	310866.4158	869140.8585	-0.550	-1.287	-1.021
3	310865.9676	869141.103	-0.379	-0.291	0.259
4	310865.7231	869140.6412	11.432	0.996	-0.438
5	310865.2817	869140.8857	1.439	-1.121	1.543
6	310865.5262	869141.3407	-0.223	-0.902	-0.107
7	310865.1051	869141.5648	7.409	0.512	-1.732
8	310864.8471	869141.1166	1.042	0.652	-1.272
9	310864.4192	869141.3543	-1.404	0.494	-0.123
10	310864.6569	869141.8161	17.615	0.074	-1.518
11	310864.2155	869142.0402	-0.911	0.547	-0.908
12	310863.971	869141.592	10.515	-0.360	-0.144
13	310863.5296	869141.8365	12.217	2.008	-1.012
14	310863.7741	869142.2847	5.625	-0.433	0.474
15	310863.3327	869142.5224	1.984	-2.537	2.584
16	310863.0882	869142.0741	0.126	0.515	0.217
17	310867.5364	869140.8382	-0.352	-0.072	-1.171
18	310867.774	869141.2796	-0.985	0.132	-0.510
19	310867.3394	869141.5241	-0.569	-0.522	-0.077
20	310867.0949	869141.0759	-0.797	0.010	-0.823
21	310866.6603	869141.3068	-1.319	1.496	-1.288
22	310866.9048	869141.755	3.617	-0.301	2.453
23	310866.4634	869141.9927	0.908	-0.378	1.105
24	310866.2189	869141.5512	-0.363	-1.244	-0.914
25	310865.7775	869141.7821	2.294	0.155	0.968
26	310866.0219	869142.2439	-1.299	-0.129	0.346
27	310865.5873	869142.468	0.587	0.992	1.110
28	310865.3292	869142.0198	-1.619	-2.344	-0.858
29	310864.9014	869142.2575	-1.815	1.364	0.116
30	310865.1459	869142.7057	-2.312	2.123	0.151
31	310864.7045	869142.9502	-1.798	1.152	-0.826
32	310864.46	869142.4952	-1.624	-1.127	-1.245
33	310864.0186	869142.7397	-0.986	-0.085	0.562
34	310864.263	869143.1879	-2.241	1.189	-1.277
35	310863.8216	869143.4256	-2.308	2.195	-0.741
36	310863.5771	869142.9774	-1.952	0.384	-1.894

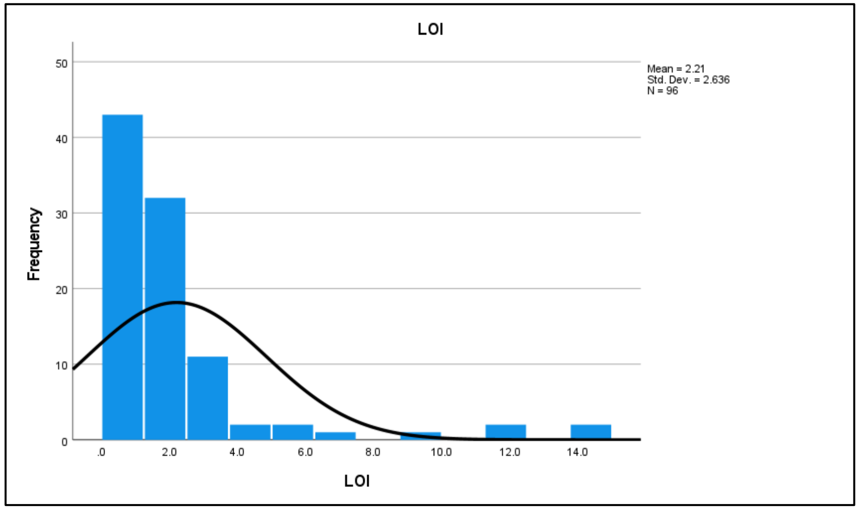
37	310868.0185	869141.7414	-0.596	-0.982	-0.071
38	310868.263	869142.1896	-2.313	2.047	0.569
39	310867.8284	869142.4273	1.021	-0.030	1.591
40	310867.5839	869141.9655	-0.267	1.767	1.110
41	310867.1425	869142.21	3.574	-1.478	2.072
42	310867.3937	869142.665	1.327	0.095	0.190
43	310866.9523	869142.9027	0.208	-0.504	0.509
44	310866.7146	869142.4477	-1.720	-0.076	-0.828
45	310866.2596	869142.6786	-1.464	0.472	-1.109
46	310866.5177	869143.1336	-2.458	-0.285	-2.624
47	310866.0695	869143.3712	-2.106	0.302	0.075
48	310865.825	869142.923	-1.791	1.884	1.911
49	310865.3972	869143.1675	-2.033	0.038	-0.166
50	310865.6348	869143.6225	-2.926	3.021	1.741
51	310865.1866	869143.8466	-1.187	-1.308	0.573
52	310864.9422	869143.3984	-1.022	0.381	0.269
53	310864.5075	869143.6361	-1.502	1.713	0.710
54	310864.7656	869144.0911	-1.509	0.179	-0.977
55	310864.3174	869144.3424	-0.703	0.198	0.336
56	310864.0661	869143.8738	-0.013	-0.645	0.510
57	310868.5075	869142.6446	-1.955	0.397	-0.967
58	310868.7384	869143.0928	0.496	-1.306	0.823
59	310868.3241	869143.3237	-1.366	-1.492	-1.540
60	310868.0796	869142.8755	-1.322	-1.097	0.107
61	310867.6382	869143.1132	0.750	-1.391	2.006
62	310867.8827	869143.5614	-1.519	-1.926	-2.015
63	310867.4413	869143.7991	-0.326	-0.097	1.462
64	310867.1968	869143.3441	-1.323	0.156	-1.107
65	310866.7486	869143.5886	-1.541	0.583	-0.075
66	310867.0067	869144.0368	-1.615	1.000	0.489
67	310866.5584	869144.2813	-1.178	-0.171	0.710
68	310866.3207	869143.8263	-0.499	0.216	0.534
69	310865.8793	869144.0639	-1.824	0.667	0.486
70	310866.117	869144.5189	-1.389	-0.869	0.040
71	310865.6892	869144.7498	-0.234	-1.045	1.261
72	310865.4311	869144.2948	-2.017	-0.368	-1.121
73	310864.9897	869144.5393	-0.481	0.732	0.413
74	310865.241	869144.9943	-1.717	1.446	-0.332
75	310864.7995	869145.232	0.184	1.927	0.904
76	310864.5551	869144.777	0.790	-0.774	1.078

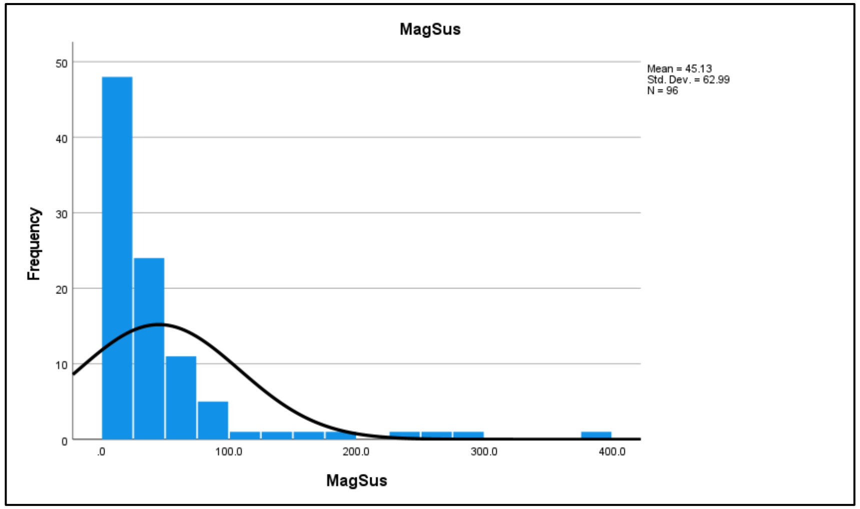
77	310868.9829	869143.5478	-1.442	0.594	0.154
78	310869.2138	869144.0164	-1.597	-2.154	-0.608
79	310868.8199	869144.2269	-2.454	-0.697	-0.389
80	310868.5754	869143.7719	-1.924	-0.613	-0.746
81	310868.134	869144.0096	-1.188	-0.146	0.247
82	310868.3717	869144.4646	-2.758	0.441	-1.289
83	310867.9302	869144.7023	-1.355	0.004	-0.803
84	310867.6858	869144.2541	-2.082	0.735	-0.629
85	310867.2443	869144.4918	-1.546	-0.716	0.194
86	310867.4956	869144.9332	-1.171	-1.019	-0.125
87	310867.0542	869145.1709	-1.425	1.531	0.804
88	310866.8097	869144.7295	-1.911	0.398	0.483
89	310866.3751	869144.9604	-1.059	-0.972	-1.225
90	310866.6128	869145.4154	-1.653	0.178	0.453
91	310866.1781	869145.6531	0.481	-1.896	-0.637
92	310865.9201	869145.1981	-1.117	-1.462	-0.100
93	310865.4922	869145.4357	1.189	-1.596	1.052
94	310865.7367	869145.8907	-0.894	-1.544	0.885
95	310865.2885	869146.1352	-0.612	0.691	1.128
96	310865.044	869145.6802	0.453	0.130	0.210

Sheet 6: Normality of geochemical and magnetic variables

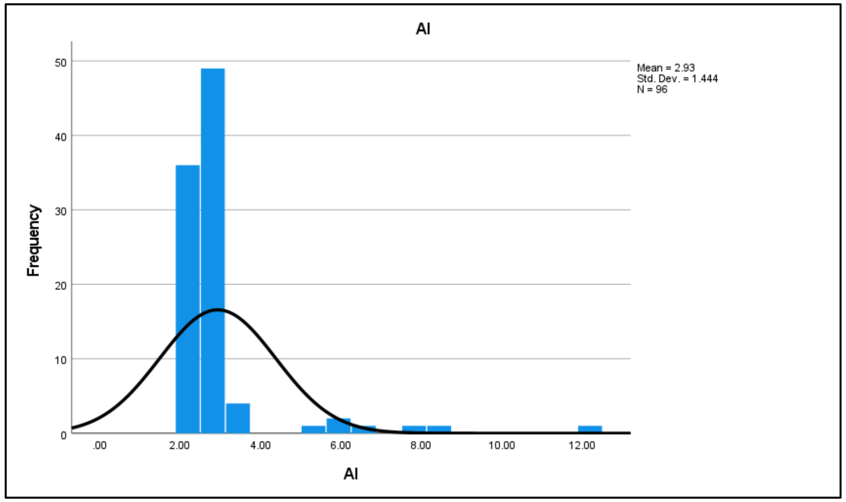


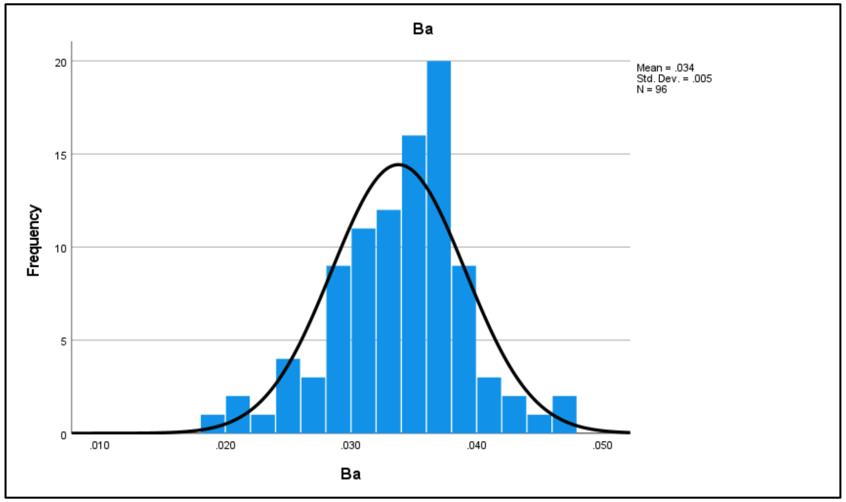


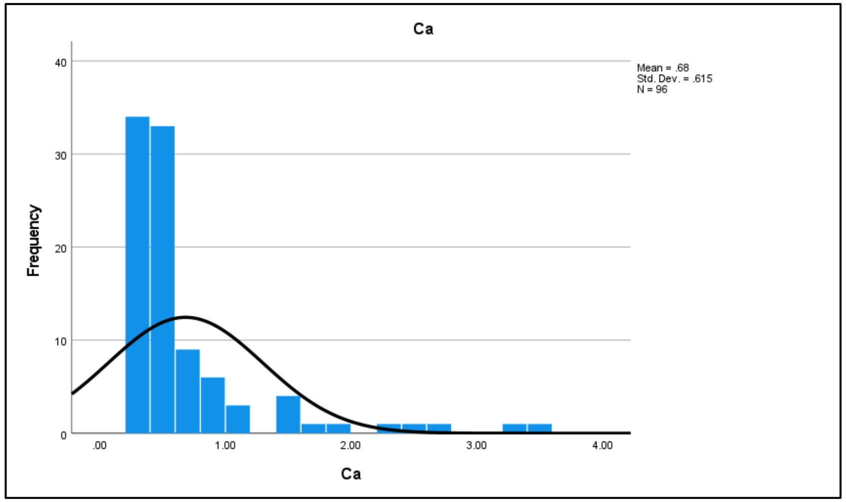


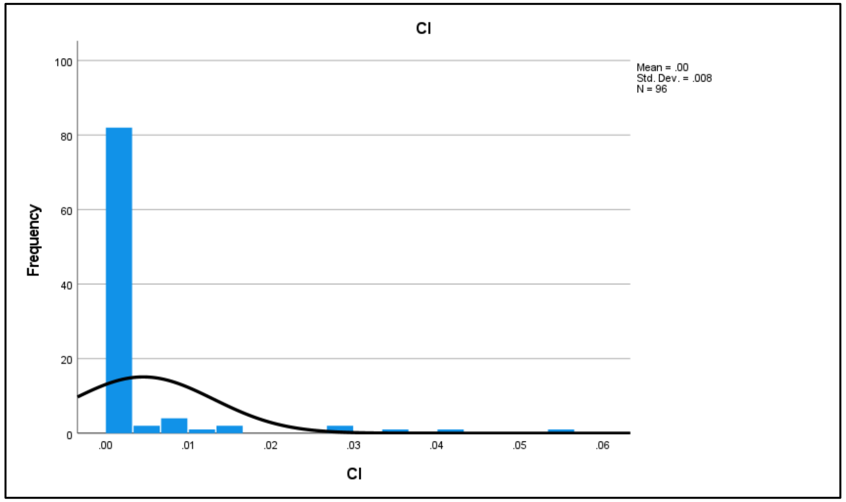


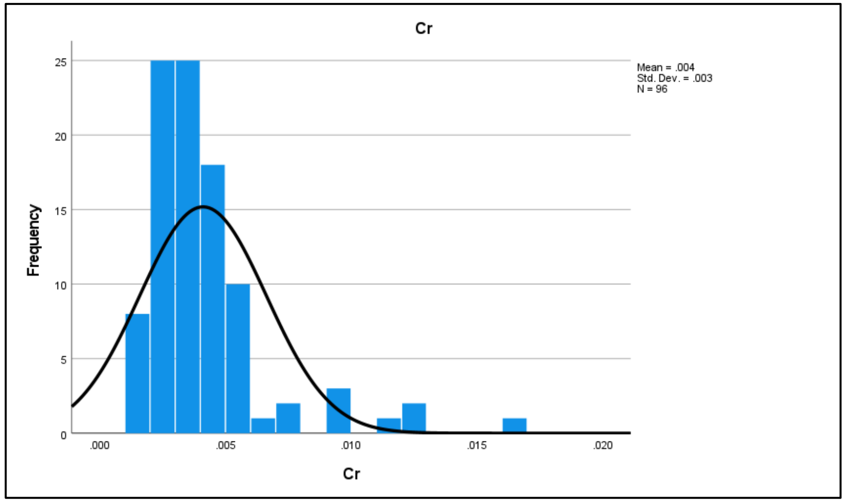
Sheet 7: Normality of multi-element variables

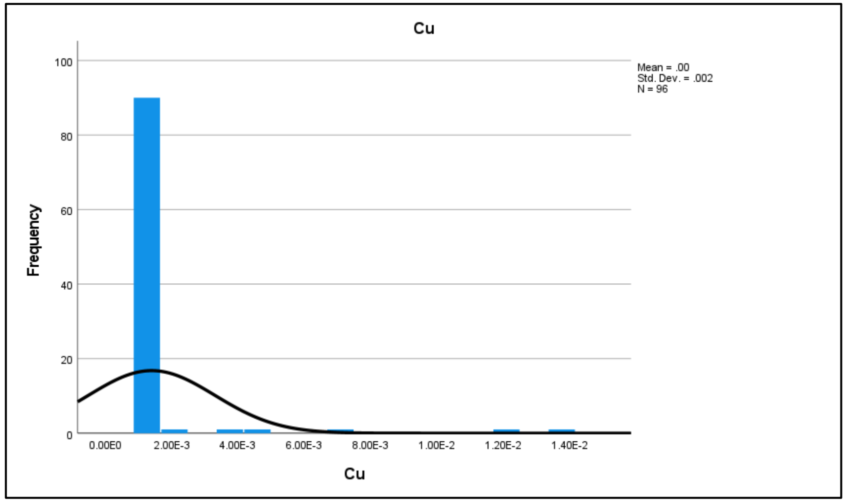


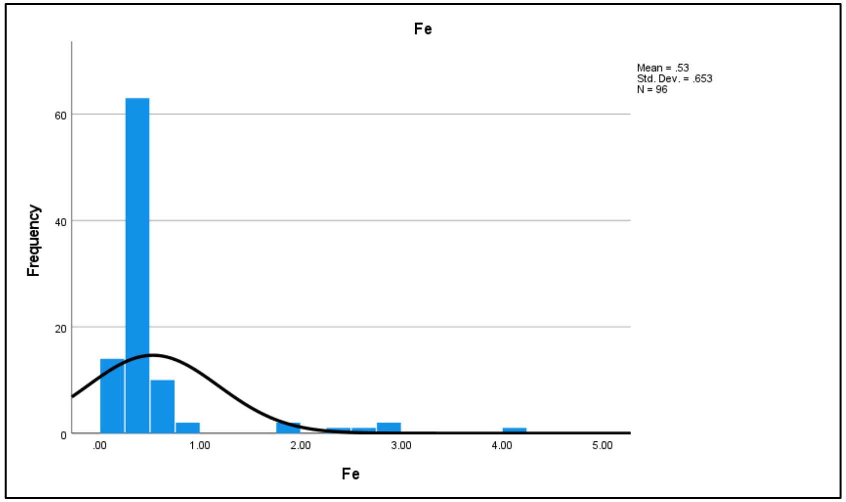


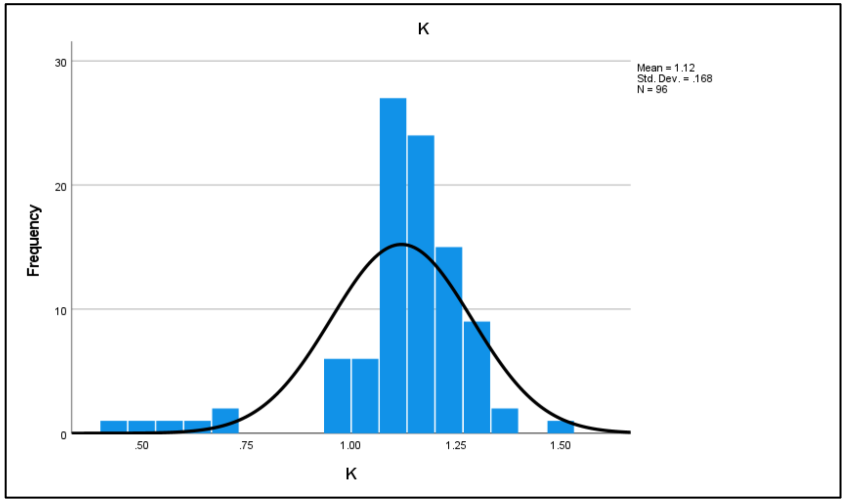


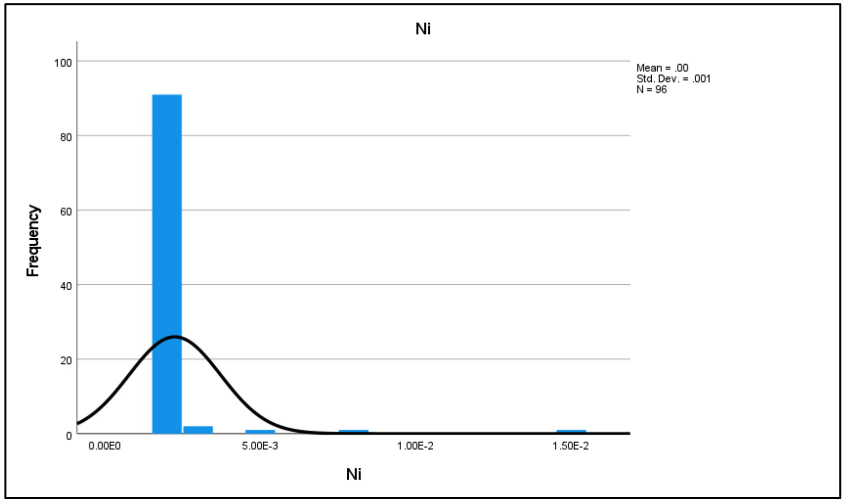
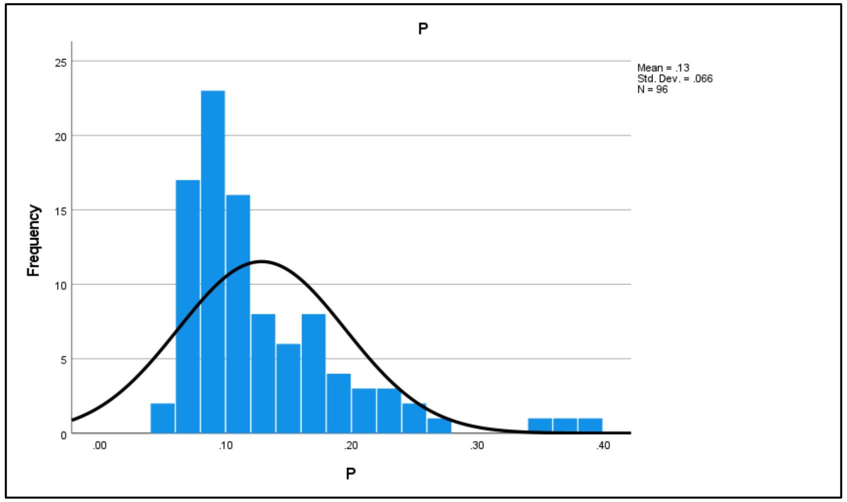
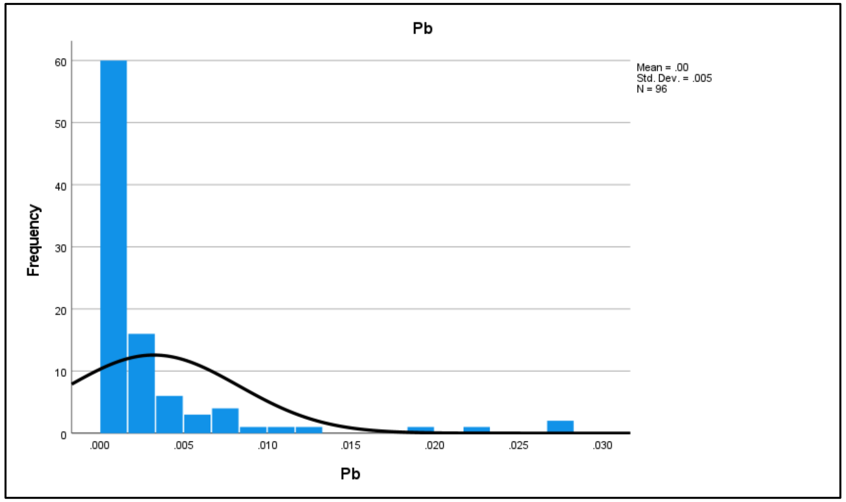
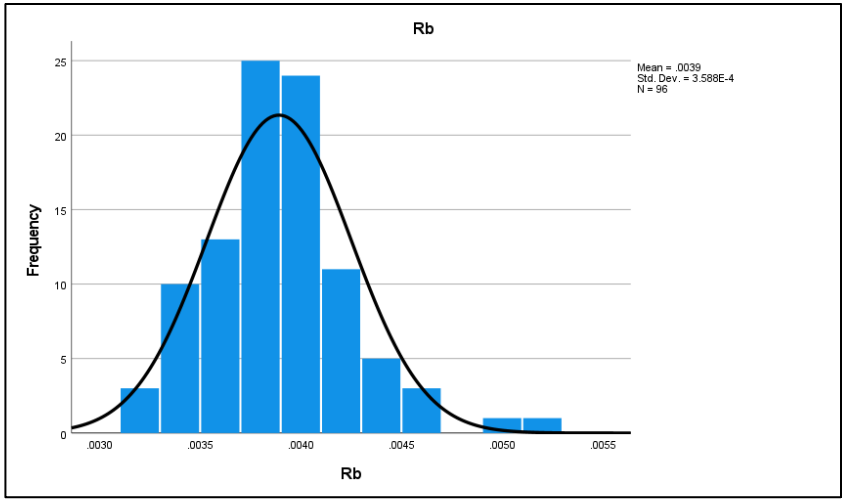


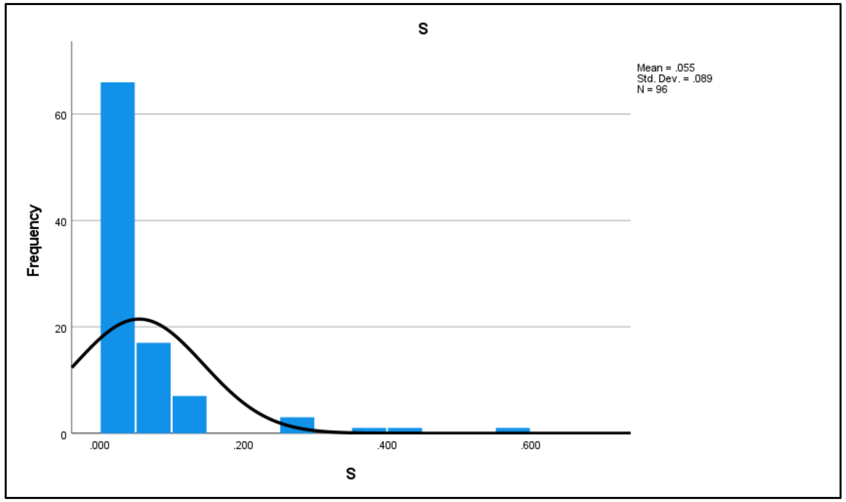

Cr
Mean = .004
Std. Dev. = .003
N = 96
Frequency
Cr

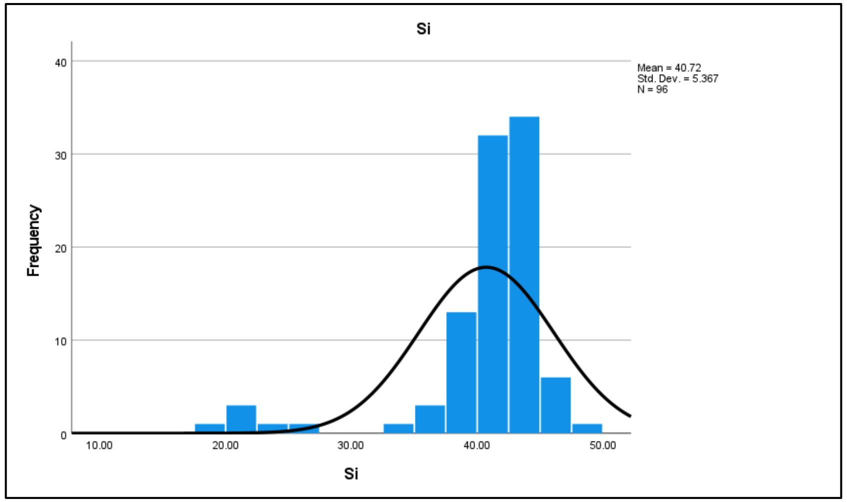

Cu
Mean = .00
Std. Dev. = .002
N = 96
Frequency
Cu

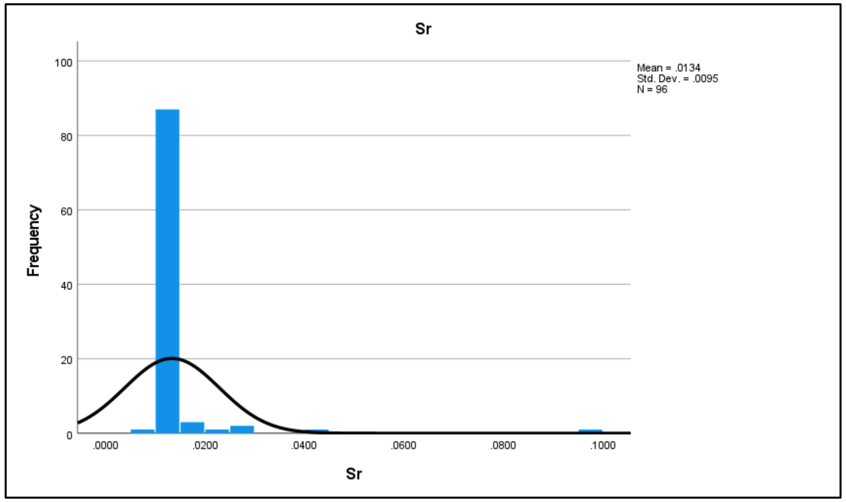

Fe
Mean = .53
Std. Dev. = .653
N = 96
Frequency
Fe

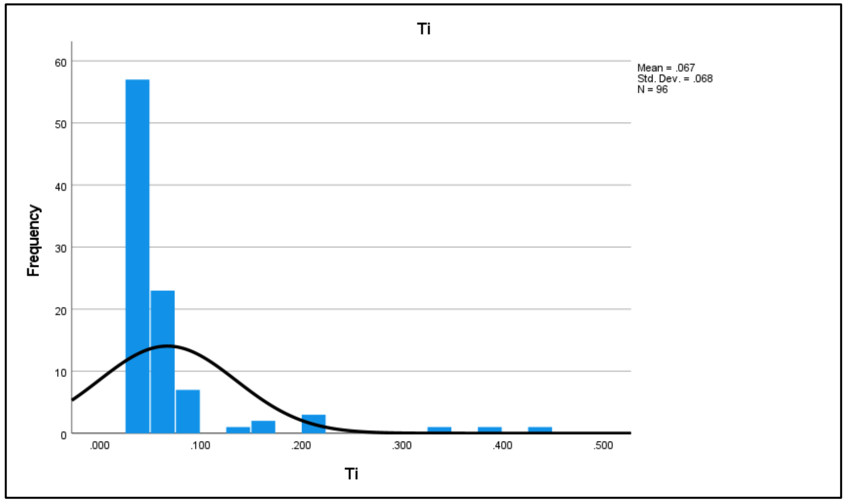

K
Mean = 1.12
Std. Dev. = .168
N = 96
Frequency
K

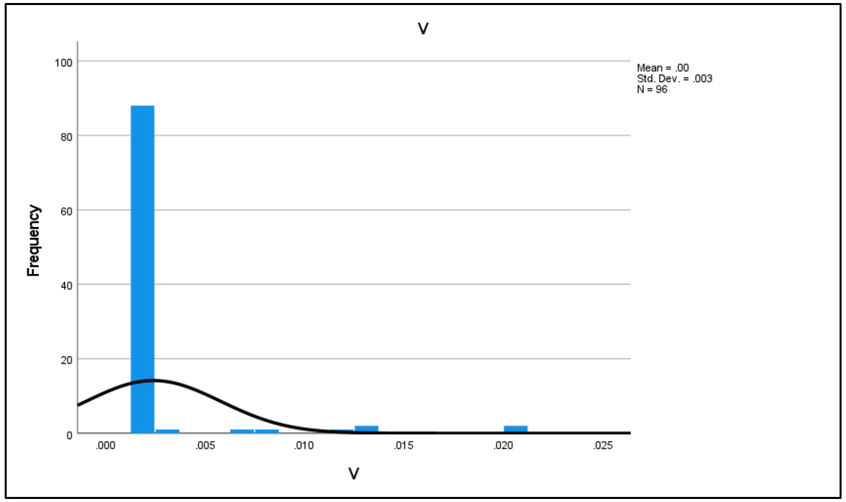

Ni
Mean = .00
Std. Dev. = .001
N = 96
Frequency
100
80
60
40
20
0
0.00E0
5.00E-3
1.00E-2
1.50E-2
Ni

P
Mean = .13
Std. Dev. = .066
N = 96
Frequency
25
20
15
10
5
0
.00
.10
.20
.30
.40
P

Pb
Mean = .00
Std. Dev. = .005
N = 96
Frequency
60
50
40
30
20
10
0
.000
.005
.010
.015
.020
.025
.030
Pb

Rb
Mean = .0039
Std. Dev. = 3.588E-4
N = 96
Frequency
25
20
15
10
5
0
.0030
.0035
.0040
.0045
.0050
.0055
Rb

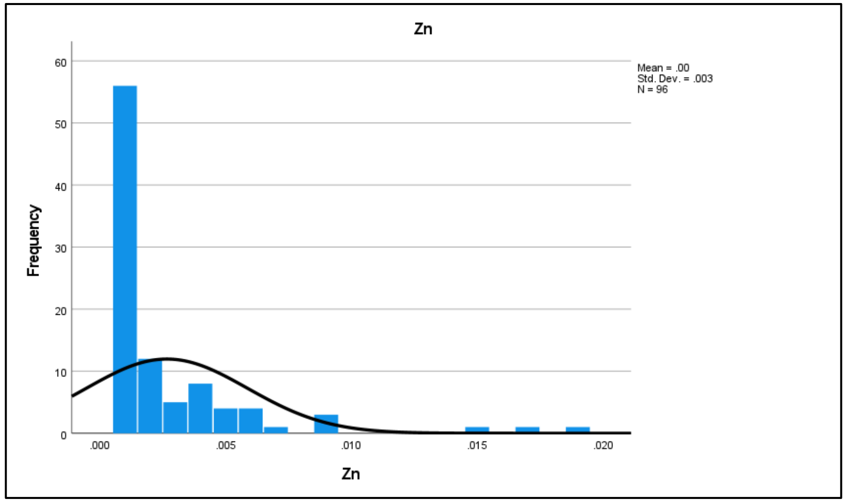

S
Mean = .055
Std. Dev. = .089
N = 96
Frequency
0
20
40
60
.000
.200
.400
.600
S

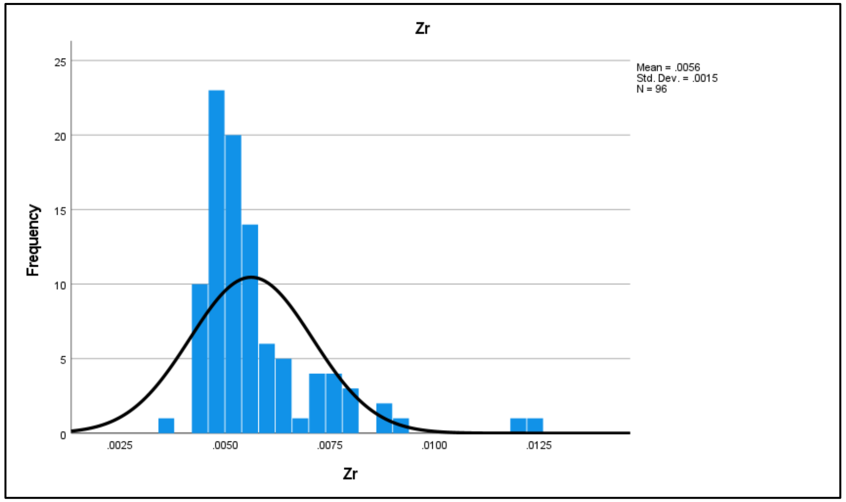

Si
Mean = 40.72
Std. Dev. = 5.367
N = 96
Frequency
0
10
20
30
40
10.00
20.00
30.00
40.00
50.00
Si


Sr
Mean = .0134
Std. Dev. = .0095
N = 96
Frequency
0
20
40
60
80
100
.0000
.0200
.0400
.0600
.0800
.1000
Sr


Ti
Mean = .067
Std. Dev. = .068
N = 96
Frequency
0
10
20
30
40
50
60
.000
.100
.200
.300
.400
.500
Ti

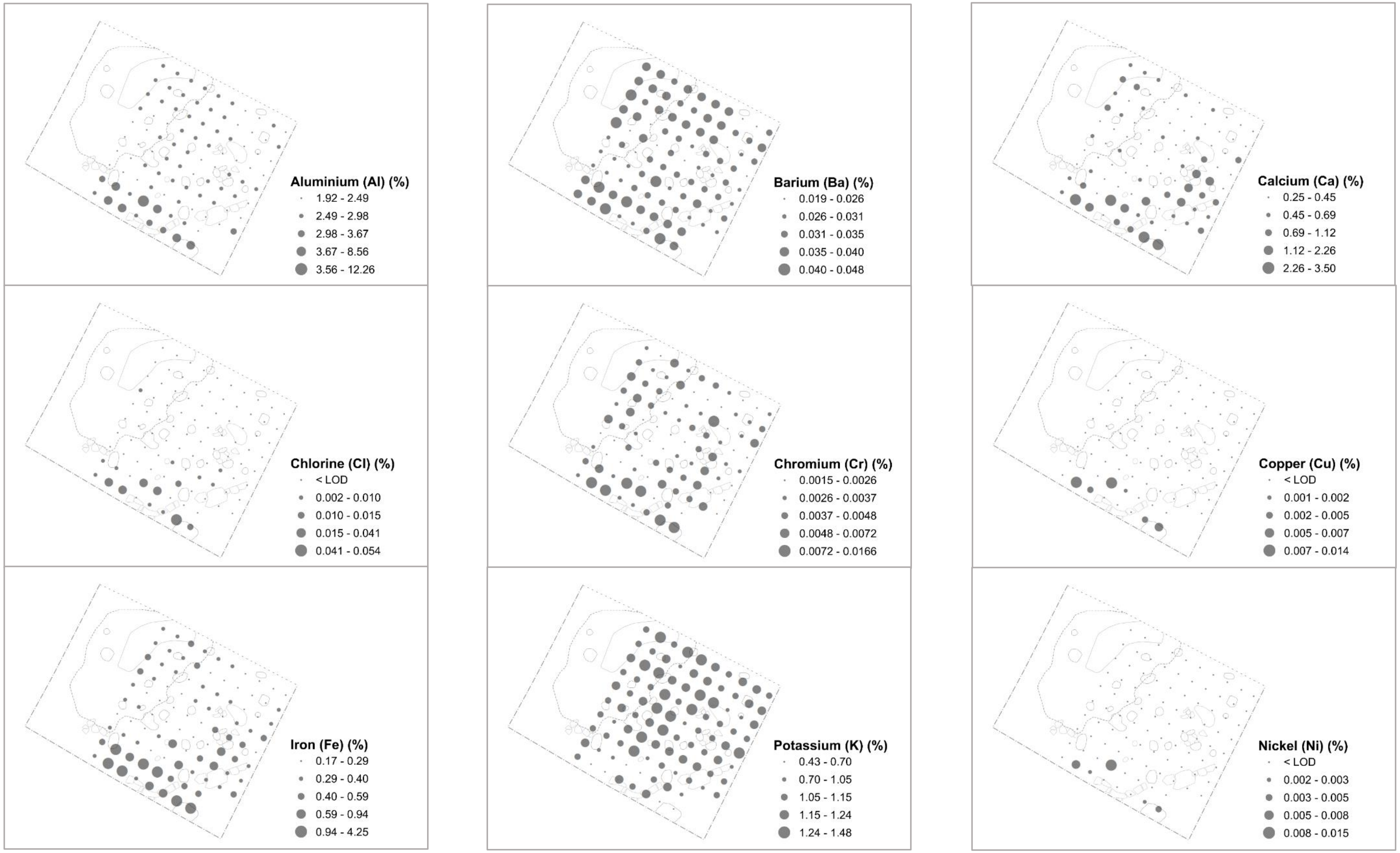

V
Mean = .00
Std. Dev. = .003
N = 96
Frequency
V

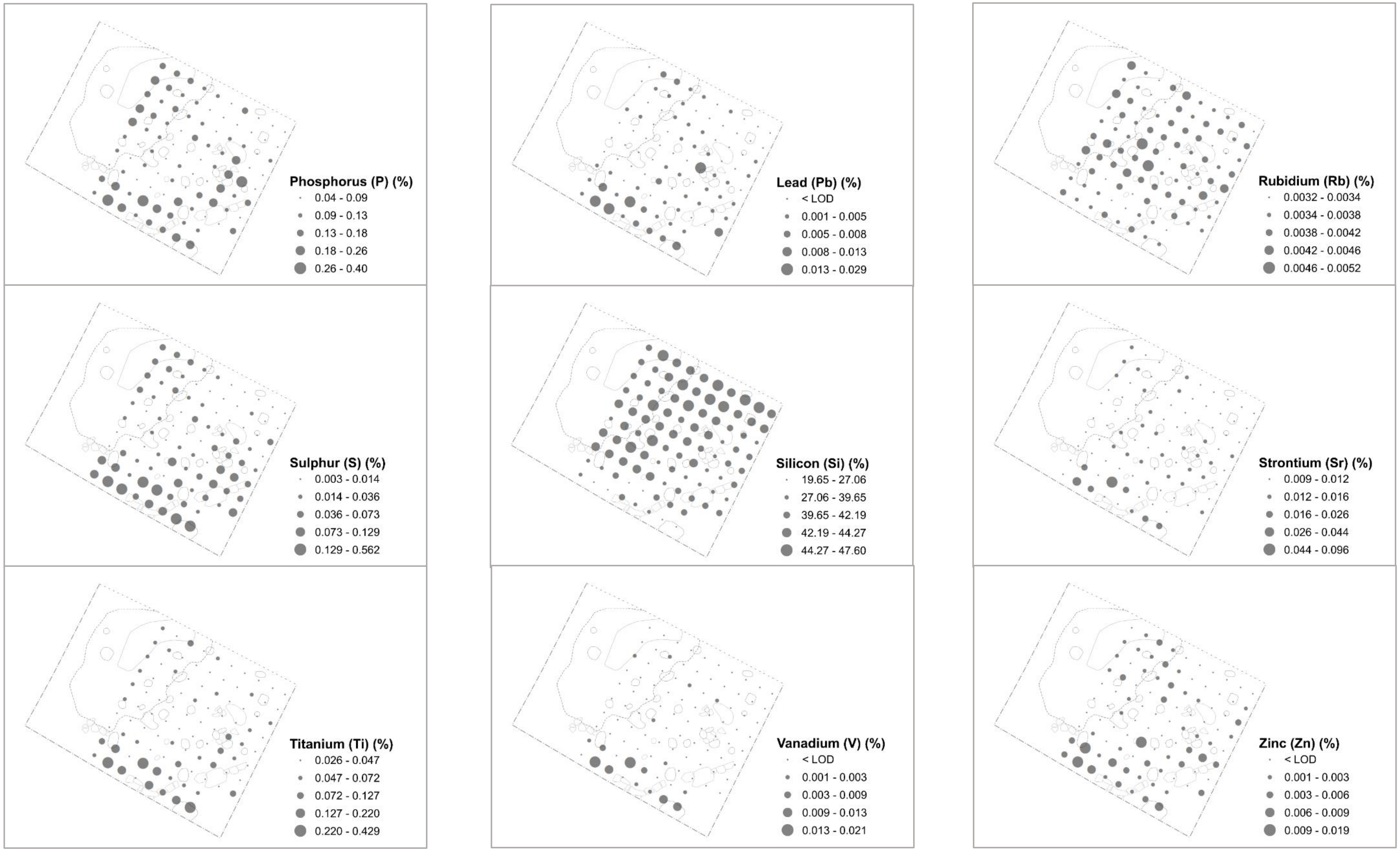

Zn
Mean = .00
Std. Dev. = .003
N = 96
Frequency
Zn

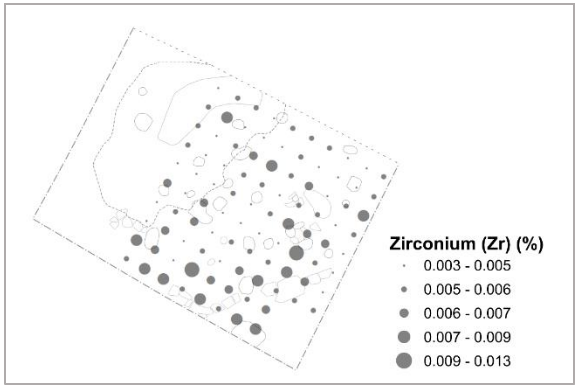

Zr
Mean = .0056
Std. Dev. = .0015
N = 96
Frequency
Zr

Sheet 8: Distribution of microrefuse, geochemical and magnetic variables

Sheet 9: Distribution of multi-element variables




Phosphorus (P) (%)
0.04 - 0.09
0.09 - 0.13
0.13 - 0.18
0.18 - 0.26
0.26 - 0.40
Lead (Pb) (%)
< LOD
0.001 - 0.005
0.005 - 0.008
0.008 - 0.013
0.013 - 0.029
Rubidium (Rb) (%)
0.0032 - 0.0034
0.0034 - 0.0038
0.0038 - 0.0042
0.0042 - 0.0046
0.0046 - 0.0052
Sulphur (S) (%)
0.003 - 0.014
0.014 - 0.036
0.036 - 0.073
0.073 - 0.129
0.129 - 0.562
Silicon (Si) (%)
19.65 - 27.06
27.06 - 39.65
39.65 - 42.19
42.19 - 44.27
44.27 - 47.60
Strontium (Sr) (%)
0.009 - 0.012
0.012 - 0.016
0.016 - 0.026
0.026 - 0.044
0.044 - 0.096
Titanium (Ti) (%)
0.026 - 0.047
0.047 - 0.072
0.072 - 0.127
0.127 - 0.220
0.220 - 0.429
Vanadium (V) (%)
< LOD
0.001 - 0.003
0.003 - 0.009
0.009 - 0.013
0.013 - 0.021
Zinc (Zn) (%)
< LOD
0.001 - 0.003
0.003 - 0.006
0.006 - 0.009
0.009 - 0.019



Zirconium (Zr) (%)
0.003 - 0.005
0.005 - 0.006
0.006 - 0.007
0.007 - 0.009
0.009 - 0.013

SM3: Microrefuse, geochemical, magnetic, multi-element and statistical data

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Sheet 1: Grid coordinates and microrefuse data

Grid	POINT X	POINT Y	Charcoal (2-30mm)	Burnt Bone (2-9mm)	Unburnt Bone	Shell	Waste Material	Fe Objects
A1	310866.6008	869145.4254	28	0	0	0	0	0
A2	310866.3707	869144.965	9	0	0	0	2	0
A3	310866.1246	869144.5205	20	0	0	0	0	0
A4	310865.8706	869144.0681	15	0	0	0	11	0
A5	310865.6325	869143.6156	0	0	0	0	0	0
A6	310865.3943	869143.1553	115	0	0	0	0	0
A7	310865.1483	869142.7108	0	0	0	0	4	0
A8	310864.9022	869142.2663	0	0	2	0	8	0
A9	310864.6641	869141.8059	0	0	0	0	18	0
A10	310864.4101	869141.3534	0	0	0	0	36	0
B1	310866.1802	869145.6556	0	0	0	0	31	0
B2	310865.9341	869145.2031	87	0	0	0	0	2
B3	310865.6801	869144.7507	34	0	0	0	0	0
B4	310865.442	869144.2983	13	0	0	0	2	0
B5	310865.1959	869143.8538	4	0	0	0	0	0
B6	310864.9498	869143.4013	23	0	0	0	0	0
B7	310864.7038	869142.9489	15	0	0	0	0	0
B8	310864.4577	869142.4964	0	2	0	0	18	0
B9	310864.2117	869142.044	0	0	0	0	0	0
B10	310863.9815	869141.5916	2	0	0	0	2	0
C1	310865.7357	869145.8937	0	2	0	0	32	0
C2	310865.4817	869145.4333	77	0	0	0	0	0
C3	310865.2435	869144.9809	19	0	0	0	7	0
C4	310864.9975	869144.5364	28	0	0	0	0	0
C5	310864.7593	869144.0919	6	1	0	0	0	0
C6	310864.5053	869143.6394	88	0	0	0	0	0
C7	310864.2672	869143.187	0	0	0	0	0	0
C8	310864.0212	869142.7266	34	0	0	0	0	2
C9	310863.7751	869142.2821	2	0	0	0	0	0
C10	310863.529	869141.8297	0	0	0	0	12	0
D1	310865.2912	869146.1318	31	0	0	0	0	0

D2	310865.0451	869145.6794	12	1	0	0	0	0
D3	310864.799	869145.219	28	0	0	0	0	0
D4	310864.5609	869144.7745	38	0	0	0	0	0
D5	310864.3148	869144.3221	0	0	0	0	0	0
D6	310864.0688	869143.8696	15	0	0	0	0	0
D7	310863.8227	869143.4251	13	0	0	0	0	0
D8	310863.5767	869142.9727	29	0	0	0	7	2
D9	310863.3385	869142.5123	24	0	0	0	18	0
D10	310863.0925	869142.0678	5	0	0	0	2	0
E1	310864.8863	869146.3382	23	0	0	0	0	0
E2	310864.6323	869145.8937	37	0	0	0	0	0
E3	310864.3942	869145.4413	13	0	0	0	0	0
E4	310864.1402	869144.9968	43	0	0	0	0	0
E5	310863.8862	869144.5443	17	0	0	0	0	0
E6	310863.6402	869144.0998	5	0	0	0	31	0
E7	310863.3941	869143.6394	2	0	0	0	5	0
E8	310863.1322	869143.1949	0	0	0	0	0	0
E9	310862.894	869142.7425	21	0	0	0	0	0
E10	310862.648	869142.3059	0	0	0	0	0	0
F1	310864.4418	869146.5843	54	0	0	0	0	0
F2	310864.1958	869146.1239	39	0	0	0	0	0
F3	310863.9418	869145.6794	20	0	0	0	0	0
F4	310863.6878	869145.2428	132	0	0	0	0	0
F5	310863.4417	869144.7904	14	0	0	0	0	0
F6	310863.1877	869144.3459	18	0	0	0	0	0
F7	310862.9417	869143.8934	20	0	0	0	0	0
F8	310862.6877	869143.441	60	0	0	0	0	0
G1	310863.9973	869146.8303	15	0	0	0	0	0
G9	310862.005	869143.2426	85	0	0	0	0	0
G10	310861.751	869142.7901	315	0	0	0	0	0
H1	310863.5528	869147.0764	17	0	0	0	0	0
H2	310863.2988	869146.6319	0	0	0	0	0	0
H3	310863.0607	869146.1794	17	0	0	0	0	0
H4	310862.8147	869145.727	35	0	0	0	0	0
H5	310862.5607	869145.2904	24	0	0	0	0	0
H6	310862.3067	869144.838	13	0	0	0	0	0
H7	310862.0527	869144.3856	28	0	0	0	0	0
H8	310861.8145	869143.9331	137	0	0	0	0	2
H9	310861.5605	869143.4886	18	0	0	0	2	2

H10	310861.3145	869143.0521	13	0	0	0	3	0
I1	310867.0533	869145.1793	6	0	0	0	6	0
I2	310866.7993	869144.7269	0	0	0	0	0	0
I3	310866.5612	869144.2824	0	0	0	0	9	0
I4	310866.3072	869143.8141	0	0	0	0	0	0
I5	310866.077	869143.3696	9	0	0	0	11	0
I6	310865.8309	869142.9251	0	0	0	0	0	0
I7	310865.5848	869142.4726	43	0	0	0	0	0
I8	310865.3467	869142.0202	0	0	0	0	0	0
I9	310865.1007	869141.5678	0	0	0	0	0	0
I10	310864.8467	869141.1153	0	0	0	0	0	0
J1	310867.4978	869144.9333	11	0	0	0	0	0
J2	310867.2517	869144.4888	2	0	0	0	0	0
J3	310867.0057	869144.0363	11	0	0	0	0	0
J4	310866.7517	869143.5839	0	0	0	0	0	0
J5	310866.5056	869143.1314	0	0	0	0	20	0
J6	310866.2754	869142.679	15	0	0	0	3	0
J7	310866.0214	869142.2266	29	0	0	0	0	0
J8	310865.7833	869141.7741	0	0	0	0	0	0
J9	310865.5452	869141.3217	0	0	0	0	0	0
J10	310865.2912	869140.8772	0	0	0	0	0	0
K1	310867.9264	869144.7031	3	0	0	0	0	0
K2	310867.6921	869144.243	14	0	0	0	8	0
K3	310867.4412	869143.7962	15	2	0	0	0	0
K4	310867.1963	869143.3433	0	0	0	0	7	0
K5	310866.9454	869142.8965	20	0	0	0	0	0
K6	310866.7128	869142.4497	0	0	0	0	0	0
K7	310866.4619	869141.9906	14	0	0	0	2	0
K8	310866.2232	869141.5438	0	0	0	0	0	0
K9	310865.9783	869141.0848	0	0	0	0	3	0
K10	310865.7396	869140.6441	0	0	0	0	0	0
L1	310868.3715	869144.4572	25	0	0	0	0	0
L2	310868.1267	869144.0104	0	0	0	0	0	0
L3	310867.8818	869143.5575	0	0	0	0	0	0
L4	310867.6492	869143.1107	0	0	0	0	0	0
L5	310867.3983	869142.6639	6	0	0	0	0	0
L6	310867.1535	869142.2049	14	10	0	0	0	0
L7	310866.9025	869141.7642	7	0	0	0	0	0
L8	310866.6577	869141.3051	0	0	0	0	0	0

L9	310866.4129	869140.8461	0	0	0	0	0	0
L10	310866.1742	869140.3993	0	0	0	0	0	0
M1	310868.806	869144.2185	0	0	0	0	0	0
M2	310868.5673	869143.7717	13	3	7	7	37	0
M3	310868.3286	869143.3188	22	0	0	0	0	0
M4	310868.0838	869142.8659	0	0	0	0	0	0
M5	310867.8267	869142.4191	11	0	0	0	2	0
M6	310867.588	869141.9662	22	0	0	0	0	0
M7	310867.3432	869141.5132	0	0	0	0	0	0
M8	310867.0984	869141.0603	0	0	0	0	0	0
M9	310866.8475	869140.6135	0	0	0	0	0	0
M10	310866.6088	869140.1606	0	0	0	0	0	0
N1	310869.2319	869144.0006	0	0	0	0	0	0
N2	310868.9896	869143.5514	0	0	0	0	14	0
N3	310868.7387	869143.0985	0	0	0	0	0	0
N4	310868.5	869142.6333	7	0	0	0	0	0
N5	310868.2613	869142.1865	0	0	0	0	0	0
N6	310868.0226	869141.7336	0	0	0	0	15	0
N7	310867.7839	869141.2868	0	0	0	0	0	0
N8	310867.5391	869140.8277	0	0	0	0	5	0
N9	310867.2881	869140.3748	0	0	0	0	0	0
N10	310867.05	869139.9276	0	0	0	0	0	0

Statistics	Charcoal	Burnt Bone	Unburnt Bone	Shell	Waste Material	Fe Objects
Mean	18	0	0	0	3	0
Median	7	0	0	0	0	0
SE	3.16	0.08	0.05	0.05	0.64	0.03
SD	36.13	0.96	0.60	0.58	7.38	0.34
Max	315	10	7	7	37	2
Min	0	0	0	0	0	0

Sheet 2: Grid coordinates, geochemical and magnetic data

Grid	POINT X	POINT Y	pH	EC	LOI	Mag sus
A1	310866.6008	869145.4254	7.0	94	2.9	18.8
A2	310866.3707	869144.965	7.0	126	0.7	9.4
A3	310866.1246	869144.5205	6.9	230	1.8	46.5
A4	310865.8706	869144.0681	7.0	143	1.3	32.9
A5	310865.6325	869143.6156	7.0	150	1.8	37.3
A6	310865.3943	869143.1553	6.9	142	1.9	24.2
A7	310865.1483	869142.7108	6.9	199	1.0	13.6
A8	310864.9022	869142.2663	7.0	142	1.5	17.9
A9	310864.6641	869141.8059	6.9	161	0.9	9.7
A10	310864.4101	869141.3534	7.1	127	1.1	9.0
B1	310866.1802	869145.6556	6.8	368	2.8	41.8
B2	310865.9341	869145.2031	6.9	288	6.9	88.3
B3	310865.6801	869144.7507	7.0	228	1.7	23.9
B4	310865.442	869144.2983	7.0	157	1.5	26.5
B5	310865.1959	869143.8538	7.1	83	2.0	18.6
B6	310864.9498	869143.4013	7.3	57	1.5	32.4
B7	310864.7038	869142.9489	7.0	99	1.9	35.7
B8	310864.4577	869142.4964	6.8	335	1.5	23.9
B9	310864.2117	869142.044	6.6	602	4.9	37.0
B10	310863.9815	869141.5916	6.9	147	1.2	7.3
C1	310865.7357	869145.8937	6.9	287	2.9	42.2
C2	310865.4817	869145.4333	6.9	245	8.3	114.5
C3	310865.2435	869144.9809	6.9	166	1.8	28.3
C4	310864.9975	869144.5364	6.9	233	2.4	61.0
C5	310864.7593	869144.0919	7.0	150	1.4	25.5
C6	310864.5053	869143.6394	6.9	172	2.0	43.0
C7	310864.2672	869143.187	7.1	97	0.8	6.4
C8	310864.0212	869142.7266	6.9	391	4.1	85.6
C9	310863.7751	869142.2821	7.0	157	1.0	7.3
C10	310863.529	869141.8297	6.9	84	0.8	9.0
D1	310865.2912	869146.1318	6.9	217	2.4	53.7
D2	310865.0451	869145.6794	7.1	162	2.0	39.4
D3	310864.799	869145.219	7.0	129	1.7	42.4
D4	310864.5609	869144.7745	6.8	323	4.6	155.8
D5	310864.3148	869144.3221	6.9	264	2.5	42.3

D6	310864.0688	869143.8696	6.9	191	2.7	78.0
D7	310863.8227	869143.4251	6.9	315	1.6	30.1
D8	310863.5767	869142.9727	7.0	145	1.1	19.8
D9	310863.3385	869142.5123	7.0	129	1.3	15.5
D10	310863.0925	869142.0678	7.0	96	0.9	9.7
E1	310864.8863	869146.3382	7.3	92	3.0	67.6
E2	310864.6323	869145.8937	6.9	145	1.7	38.3
E3	310864.3942	869145.4413	7.0	167	2.3	52.7
E4	310864.1402	869144.9968	6.9	299	5.8	171.3
E5	310863.8862	869144.5443	6.9	240	2.8	154.4
E6	310863.6402	869144.0998	6.9	224	2.3	47.5
E7	310863.3941	869143.6394	7.0	147	0.9	10.1
E8	310863.1322	869143.1949	7.0	92	0.7	11.7
E9	310862.894	869142.7425	7.0	135	0.9	10.4
E10	310862.648	869142.3059	7.0	170	1.0	12.3
F1	310864.4418	869146.5843	7.1	171	2.0	30.3
F2	310864.1958	869146.1239	7.0	184	3.1	76.9
F3	310863.9418	869145.6794	7.0	197	2.7	63.5
F4	310863.6878	869145.2428	6.8	461	7.3	206.5
F5	310863.4417	869144.7904	7.0	295	4.6	123.9
F6	310863.1877	869144.3459	7.0	206	2.5	85.4
F7	310862.9417	869143.8934	7.0	199	1.7	38.7
F8	310862.6877	869143.441	7.0	142	2.2	55.1
G1	310863.9973	869146.8303	7.1	111	1.7	38.3
G9	310862.005	869143.2426	7.0	121	3.1	45.9
G10	310861.751	869142.7901	7.0	104	5.7	60.7
H1	310863.5528	869147.0764	7.0	134	1.5	23.0
H2	310863.2988	869146.6319	6.9	146	2.5	38.7
H3	310863.0607	869146.1794	6.9	184	2.3	74.7
H4	310862.8147	869145.727	7.1	59	1.4	31.8
H5	310862.5607	869145.2904	7.1	131	1.5	37.9
H6	310862.3067	869144.838	7.1	67	1.3	40.1
H7	310862.0527	869144.3856	7.0	154	1.9	58.0
H8	310861.8145	869143.9331	7.1	166	1.8	47.1
H9	310861.5605	869143.4886	7.0	213	1.9	59.5
H10	310861.3145	869143.0521	7.1	162	1.6	53.2
I1	310867.0533	869145.1793	7.1	62	0.8	9.9
I2	310866.7993	869144.7269	7.1	64	0.9	9.9
I3	310866.5612	869144.2824	6.9	143	0.8	14.1

I4	310866.3072	869143.8141	7.2	88	0.8	8.8
I5	310866.077	869143.3696	7.1	109	1.1	15.5
I6	310865.8309	869142.9251	7.2	70	0.8	11.4
I7	310865.5848	869142.4726	7.1	172	1.6	25.4
I8	310865.3467	869142.0202	7.4	29	0.5	2.3
I9	310865.1007	869141.5678	7.3	54	0.5	3.6
I10	310864.8467	869141.1153	7.2	38	0.5	3.1
J1	310867.4978	869144.9333	7.1	127	1.0	10.5
J2	310867.2517	869144.4888	7.2	60	0.7	5.0
J3	310867.0057	869144.0363	7.0	129	1.1	19.5
J4	310866.7517	869143.5839	7.0	87	0.7	9.9
J5	310866.5056	869143.1314	7.0	82	0.9	9.4
J6	310866.2754	869142.679	6.9	281	1.8	30.8
J7	310866.0214	869142.2266	6.9	241	1.4	18.8
J8	310865.7833	869141.7741	7.3	24	0.3	3.5
J9	310865.5452	869141.3217	7.3	43	0.5	2.7
J10	310865.2912	869140.8772	7.1	51	0.5	2.4
K1	310867.9264	869144.7031	7.2	87	0.8	7.0
K2	310867.6921	869144.243	7.1	107	1.0	8.3
K3	310867.4412	869143.7962	7.0	178	1.1	26.2
K4	310867.1963	869143.3433	7.1	65	0.6	6.4
K5	310866.9454	869142.8965	7.2	139	1.9	51.0
K6	310866.7128	869142.4497	7.0	112	0.5	3.1
K7	310866.4619	869141.9906	6.9	144	1.3	35.3
K8	310866.2232	869141.5438	7.3	45	0.7	3.0
K9	310865.9783	869141.0848	6.9	225	1.4	48.4
K10	310865.7396	869140.6441	7.2	84	1.6	20.9
L1	310868.3715	869144.4572	7.2	47	0.8	6.7
L2	310868.1267	869144.0104	7.2	44	0.6	7.5
L3	310867.8818	869143.5575	7.1	47	0.6	5.9
L4	310867.6492	869143.1107	7.3	52	0.8	8.3
L5	310867.3983	869142.6639	6.9	113	1.7	52.9
L6	310867.1535	869142.2049	6.9	114	1.6	20.5
L7	310866.9025	869141.7642	7.1	76	0.9	12.8
L8	310866.6577	869141.3051	6.8	244	2.1	8.3
L9	310866.4129	869140.8461	6.9	96	1.3	25.4
L10	310866.1742	869140.3993	7.1	100	1.1	20.2
M1	310868.806	869144.2185	7.3	45	0.7	6.2
M2	310868.5673	869143.7717	7.0	55	1.9	78.6

M3	310868.3286	869143.3188	6.9	144	1.5	34.2
M4	310868.0838	869142.8659	7.1	80	0.6	5.3
M5	310867.8267	869142.4191	7.2	95	1.3	19.4
M6	310867.588	869141.9662	7.0	109	1.3	32.8
M7	310867.3432	869141.5132	7.1	80	0.8	23.4
M8	310867.0984	869141.0603	7.0	139	1.4	11.7
M9	310866.8475	869140.6135	7.2	38	0.6	6.3
M10	310866.6088	869140.1606	7.2	35	0.6	2.3
N1	310869.2319	869144.0006	7.2	53	0.5	5.0
N2	310868.9896	869143.5514	7.1	70	0.6	5.2
N3	310868.7387	869143.0985	7.1	78	0.5	2.6
N4	310868.5	869142.6333	6.9	100	0.8	7.7
N5	310868.2613	869142.1865	6.9	218	1.5	23.1
N6	310868.0226	869141.7336	7.0	170	1.2	5.5
N7	310867.7839	869141.2868	7.0	112	1.3	8.1
N8	310867.5391	869140.8277	7.2	54	0.6	4.1
N9	310867.2881	869140.3748	6.8	293	1.9	6.6
N10	310867.05	869139.9276	7.3	37	0.7	3.3

Statistics	**pH**	**EC**	**LOI**	**Mag sus**
Mean	7.0	146.8	1.7	32.2
Median	7.0	134.0	1.4	23.0
SE	0.01	8.02	0.12	3.05
SD	0.14	91.75	1.34	34.87
Max	7.4	602	8.3	206.5
Min	6.6	24	0.3	2.3

Sheet 3: Multi-element data

Grid	Al	Ba	Ca	Cr[1]	Fe	K	P	Rb	S[2]	Si	Sr	Ti	Zr	Cl[3]*	Pb[4]*	Zn[5]*
A1	2.7332	0.0350	0.6436	0.0068	0.3470	1.1950	0.0914	0.0040	0.0190	38.4162	0.0136	0.0378	0.0058	0.0020	0.0012	0.0012
A2	2.8514	0.0298	0.3766	0.0034	0.2764	1.2008	0.1002	0.0034	0.0118	44.9774	0.0106	0.0492	0.0046	0.0020	0.0010	0.0018
A3	2.8558	0.0292	0.7126	0.0052	0.3322	1.1728	0.1536	0.0038	0.0428	43.2616	0.0124	0.0500	0.0052	0.0020	0.0016	0.0036
A4	2.8998	0.0310	0.5224	0.0046	0.3098	1.2202	0.1304	0.0042	0.0270	44.3856	0.0126	0.0454	0.0042	0.0020	0.0012	0.0020
A5	3.3596	0.0338	0.7932	0.0066	0.3748	1.2802	0.1540	0.0038	0.0474	44.1964	0.0130	0.0528	0.0046	0.0020	0.0010	0.0016
A6	2.8652	0.0354	0.8114	0.0076	0.4146	1.2676	0.1532	0.0044	0.0346	41.6830	0.0128	0.0510	0.0044	0.0020	0.0012	0.0010
A7	2.9658	0.0258	0.3960	0.0042	0.2876	1.2536	0.0958	0.0040	0.0166	44.8364	0.0120	0.0678	0.0060	0.0020	0.0010	0.0010
A8	3.1422	0.0312	0.9418	0.0054	0.2924	1.2594	0.4216	0.0038	0.0262	45.3576	0.0120	0.0524	0.0048	0.0020	0.0010	0.0010
A9	3.6406	0.0266	0.4694	0.0140	0.2884	1.5656	0.1020	0.0044	0.0160	47.4902	0.0124	0.0364	0.0052	0.0020	0.0010	0.0010
A10	3.3510	0.0342	0.5730	0.0058	0.3390	1.4028	0.1136	0.0042	0.0426	47.8042	0.0116	0.0532	0.0072	0.0020	0.0014	0.0010
B1	3.2554	0.0382	0.6474	0.0052	0.4568	1.3248	0.1406	0.0038	0.0806	45.8004	0.0118	0.0836	0.0052	0.0020	0.0064	0.0068
B2	2.8560	0.0362	2.1404	0.0086	0.5446	1.1114	0.2562	0.0040	0.1640	35.1548	0.0160	0.0770	0.0094	0.0256	0.0020	0.0022
B3	3.1812	0.0350	0.6058	0.0030	0.2886	1.2972	0.1432	0.0042	0.0320	46.7026	0.0122	0.0432	0.0050	0.0020	0.0010	0.0012
B4	3.0294	0.0352	0.5292	0.0056	0.3314	1.1914	0.1092	0.0040	0.0214	46.7214	0.0116	0.0478	0.0052	0.0020	0.0010	0.0014
B5	3.6374	0.0348	0.8014	0.0050	0.3066	1.4466	0.2220	0.0042	0.0812	45.6488	0.0128	0.0484	0.0044	0.0020	0.0012	0.0010
B6	2.7534	0.0276	0.5272	0.0036	0.3160	1.0804	0.1178	0.0040	0.0272	43.7632	0.0112	0.0416	0.0052	0.0020	0.0010	0.0010
B7	2.9258	0.0384	0.8976	0.0049	0.3444	1.2556	0.2958	0.0042	0.0740	43.8336	0.0116	0.0544	0.0054	0.0020	0.0012	0.0018
B8	3.2612	0.0370	0.5026	0.0032	0.3726	1.3200	0.1082	0.0038	0.0416	47.6464	0.0116	0.0708	0.0052	0.0020	0.0014	0.0014
B9	2.6158	0.0226	1.1964	0.0078	0.4516	1.1368	0.0934	0.0044	0.2248	40.8542	0.0124	0.0586	0.0064	0.0050	0.0018	0.0020
B10	2.6010	0.0322	0.6972	0.0058	0.2718	1.2482	0.1942	0.0036	0.0212	47.5278	0.0112	0.0454	0.0054	0.0020	0.0012	0.0010
C1	3.6506	0.0380	0.6110	0.0043	0.4066	1.2678	0.1476	0.0034	0.0838	46.3896	0.0118	0.0552	0.0052	0.0020	0.0058	0.0056
C2	3.0482	0.0364	2.0928	0.0066	0.6152	1.1624	0.2672	0.0040	0.1398	37.5694	0.0170	0.1302	0.0078	0.0210	0.0010	0.0018
C3	3.2110	0.0322	0.5386	0.0035	0.3890	1.4526	0.1520	0.0042	0.0626	47.6108	0.0130	0.0524	0.0044	0.0020	0.0010	0.0020
C4	3.2140	0.0344	0.7336	0.0050	0.3576	1.3702	0.1778	0.0042	0.0506	45.7306	0.0118	0.0774	0.0060	0.0038	0.0010	0.0010
C5	3.1658	0.0380	0.4896	0.0036	0.2950	1.4840	0.1520	0.0040	0.0240	48.1636	0.0120	0.0410	0.0046	0.0020	0.0010	0.0010
C6	2.8948	0.0256	0.6368	0.0048	0.3226	1.2716	0.1382	0.0040	0.0398	43.5324	0.0116	0.0546	0.0048	0.0020	0.0010	0.0010
C7	3.4502	0.0382	0.4100	0.0062	0.3012	1.4580	0.1042	0.0042	0.0066	48.7818	0.0114	0.0470	0.0048	0.0020	0.0010	0.0010

[1] Non-detect substituted with LOD/2 = 0.0015
[2] Non-detect substituted with LOD/2 = 0.0030
[3] Non-detect substituted with LOD/2 = 0.0020
[4] Non-detect substituted with LOD/2 = 0.0010
[5] Non-detect substituted with LOD/2 = 0.0010
* Elements with number of non-detect values greater than 25%

C8	3.0826	0.0246	1.1446	0.0062	0.5840	1.2532	0.2248	0.0040	0.1070	43.7234	0.0116	0.0640	0.0060	0.0138	0.0010	0.0010
C9	3.1056	0.0326	0.3968	0.0037	0.3602	1.2874	0.1200	0.0040	0.0344	48.5788	0.0100	0.0610	0.0048	0.0020	0.0010	0.0010
C10	3.0748	0.0274	0.3724	0.0015	0.2554	1.1966	0.0668	0.0038	0.0030	54.8476	0.0108	0.0384	0.0058	0.0020	0.0010	0.0010
D1	2.5068	0.0338	0.6464	0.0030	0.3492	1.1078	0.1572	0.0038	0.0402	39.6154	0.0120	0.0504	0.0054	0.0020	0.0010	0.0010
D2	2.5268	0.0206	0.8080	0.0036	0.3282	1.0718	0.1502	0.0036	0.0460	39.0944	0.0120	0.0524	0.0052	0.0026	0.0010	0.0010
D3	2.6106	0.0316	0.5964	0.0046	0.3702	1.2096	0.1256	0.0038	0.0280	41.9082	0.0120	0.0484	0.0050	0.0020	0.0010	0.0010
D4	2.6468	0.0408	1.0536	0.0054	0.6094	1.1006	0.2352	0.0044	0.0668	40.4076	0.0132	0.0748	0.0064	0.0074	0.0012	0.0014
D5	2.6618	0.0248	0.6356	0.0038	0.3584	1.0732	0.1834	0.0040	0.0452	42.4248	0.0110	0.0512	0.0064	0.0020	0.0010	0.0010
D6	2.6978	0.0258	0.6652	0.0048	0.5430	1.1480	0.1934	0.0036	0.0468	42.9402	0.0110	0.0566	0.0068	0.0020	0.0010	0.0010
D7	2.7206	0.0342	0.5738	0.0039	0.3440	1.1368	0.1528	0.0038	0.0242	44.0226	0.0126	0.0490	0.0060	0.0020	0.0010	0.0012
D8	2.8708	0.0352	0.4242	0.0056	0.3280	1.2552	0.1178	0.0038	0.0234	46.4894	0.0112	0.0400	0.0068	0.0020	0.0010	0.0010
D9	3.1572	0.0294	0.4896	0.0029	0.4320	1.2482	0.1170	0.0038	0.0250	48.6452	0.0110	0.0462	0.0060	0.0020	0.0020	0.0010
D10	3.0192	0.0352	0.3720	0.0023	0.3042	1.3786	0.1192	0.0040	0.0150	47.2188	0.0116	0.0550	0.0046	0.0020	0.0010	0.0012
E1	3.0872	0.0306	1.2904	0.0044	0.4270	1.2604	0.1766	0.0042	0.0866	42.4336	0.0138	0.0588	0.0052	0.0020	0.0010	0.0010
E2	3.1560	0.0284	0.8978	0.0068	0.3346	1.1110	0.1716	0.0038	0.0314	44.5940	0.0134	0.0548	0.0044	0.0020	0.0010	0.0010
E3	3.1738	0.0362	0.7992	0.0033	0.3636	1.2098	0.1812	0.0038	0.0462	46.0282	0.0128	0.0518	0.0060	0.0020	0.0010	0.0010
E4	3.8074	0.0372	1.2778	0.0043	0.5566	1.7204	0.2374	0.0054	0.0890	41.6376	0.0130	0.1006	0.0066	0.0070	0.0012	0.0022
E5	3.0882	0.0274	0.7424	0.0072	0.4994	1.3130	0.1452	0.0042	0.0368	44.1384	0.0140	0.0644	0.0050	0.0020	0.0010	0.0010
E6	4.1800	0.0350	0.8978	0.0028	0.4138	1.2900	0.2460	0.0040	0.0952	46.3700	0.0118	0.0892	0.0058	0.0020	0.0036	0.0060
E7	3.1074	0.0282	0.3476	0.0030	0.2518	1.4494	0.1152	0.0040	0.0138	47.5248	0.0120	0.0386	0.0048	0.0020	0.0010	0.0010
E8	2.7968	0.0288	0.3572	0.0029	0.2652	1.1552	0.1086	0.0038	0.0030	47.4864	0.0114	0.0400	0.0052	0.0020	0.0010	0.0010
E9	3.0304	0.0284	0.3920	0.0026	0.2574	1.2142	0.1056	0.0038	0.0128	47.9596	0.0118	0.0440	0.0050	0.0020	0.0010	0.0012
E10	3.0618	0.0318	0.3634	0.0050	0.2864	1.3506	0.1110	0.0038	0.0126	48.4902	0.0116	0.0440	0.0048	0.0020	0.0010	0.0010
F1	3.2394	0.0378	0.8220	0.0040	0.3108	1.2344	0.1884	0.0040	0.0532	47.4008	0.0126	0.0490	0.0058	0.0030	0.0010	0.0012
F2	3.3782	0.0240	0.9194	0.0062	0.3658	1.2874	0.1874	0.0038	0.0630	46.3778	0.0134	0.0560	0.0052	0.0020	0.0016	0.0010
F3	3.0740	0.0412	1.1072	0.0088	0.4080	1.1510	0.1664	0.0038	0.0634	44.6128	0.0132	0.0636	0.0050	0.0020	0.0010	0.0010
F4	3.5712	0.0346	2.8136	0.0070	0.7316	1.1528	0.3112	0.0040	0.1694	33.1684	0.0176	0.1216	0.0098	0.0378	0.0090	0.0046
F5	3.1964	0.0316	1.5310	0.0064	0.5056	1.2984	0.2368	0.0044	0.0832	39.9032	0.0154	0.1006	0.0058	0.0162	0.0010	0.0022
F6	3.2126	0.0358	1.0612	0.0040	0.4916	1.4320	0.2090	0.0040	0.0676	43.8006	0.0184	0.0726	0.0056	0.0068	0.0010	0.0012
F7	2.8962	0.0346	0.5664	0.0064	0.3324	1.2122	0.1204	0.0040	0.0120	44.5918	0.0122	0.0494	0.0066	0.0020	0.0010	0.0010
F8	3.5098	0.0392	1.1700	0.0050	0.3892	1.4292	0.2238	0.0042	0.0572	44.5470	0.0136	0.0594	0.0060	0.0034	0.0032	0.0012
G1	3.1294	0.0324	0.8252	0.0037	0.3362	1.3110	0.2252	0.0042	0.0454	46.6760	0.0138	0.0580	0.0052	0.0030	0.0010	0.0010
G9	3.6054	0.0342	2.9060	0.0066	0.5802	1.2390	0.4024	0.0042	0.0966	40.0364	0.0156	0.1000	0.0062	0.0118	0.0042	0.0010
G10	2.9990	0.0338	4.1180	0.0088	0.6760	1.1322	0.3532	0.0048	0.1408	34.2098	0.0160	0.0862	0.0076	0.0328	0.0032	0.0010
H1	2.7282	0.0182	0.5228	0.0031	0.2844	1.1332	0.1420	0.0040	0.0170	47.5638	0.0120	0.0464	0.0060	0.0020	0.0010	0.0010
H2	3.4554	0.0370	1.0248	0.0056	0.3792	1.4038	0.2222	0.0040	0.0800	45.2744	0.0134	0.0702	0.0068	0.0020	0.0012	0.0010
H3	3.3194	0.0338	0.9450	0.0078	0.3872	1.3342	0.1648	0.0040	0.0526	44.5812	0.0124	0.0714	0.0050	0.0020	0.0010	0.0010
H4	3.0878	0.0336	0.5676	0.0044	0.3218	1.3192	0.1028	0.0040	0.0124	47.5730	0.0118	0.0486	0.0054	0.0020	0.0012	0.0010
H5	3.1556	0.0288	0.7518	0.0042	0.3324	1.3208	0.1178	0.0044	0.0290	48.0752	0.0118	0.0718	0.0054	0.0020	0.0014	0.0010
H6	2.9306	0.0316	0.5870	0.0038	0.3766	1.3632	0.1216	0.0048	0.0216	48.2914	0.0122	0.0506	0.0056	0.0020	0.0010	0.0010

H7	2.9452	0.0260	0.7622	0.0044	0.3332	1.3418	0.1056	0.0044	0.0300	46.0960	0.0122	0.0778	0.0068	0.0020	0.0010	0.0010
H8	2.7500	0.0304	0.8490	0.0042	0.3484	1.1938	0.1184	0.0040	0.0186	46.8728	0.0118	0.0426	0.0062	0.0020	0.0014	0.0010
H9	2.8572	0.0314	0.6398	0.0040	0.3146	1.3744	0.1176	0.0044	0.0228	47.0542	0.0118	0.0632	0.0082	0.0020	0.0012	0.0010
H10	3.1026	0.0304	0.6924	0.0031	0.2958	1.3452	0.0968	0.0040	0.0218	47.4288	0.0108	0.0506	0.0054	0.0020	0.0012	0.0010
I1	3.1372	0.0320	0.4370	0.0029	0.2792	1.2786	0.1216	0.0040	0.0096	47.5702	0.0120	0.0388	0.0064	0.0020	0.0010	0.0010
I2	2.6222	0.0264	0.3568	0.0021	0.2808	1.2406	0.1048	0.0042	0.0110	48.8894	0.0118	0.0498	0.0044	0.0020	0.0010	0.0012
I3	2.3674	0.0350	0.4346	0.0036	0.2832	1.1642	0.0932	0.0038	0.0136	41.0610	0.0114	0.0312	0.0054	0.0020	0.0024	0.0028
I4	2.4706	0.0332	0.3518	0.0018	0.2848	1.0816	0.0898	0.0038	0.0116	43.1440	0.0116	0.0360	0.0048	0.0020	0.0010	0.0014
I5	2.7738	0.0370	0.4638	0.0021	0.2474	1.2544	0.0996	0.0038	0.0220	42.8528	0.0118	0.0550	0.0050	0.0020	0.0010	0.0012
I6	2.0072	0.0260	0.3016	0.0019	0.2274	0.9914	0.0634	0.0038	0.0030	40.4622	0.0116	0.0336	0.0072	0.0020	0.0010	0.0010
I7	2.9470	0.0274	0.7906	0.0031	0.6268	1.2168	0.1110	0.0040	0.1110	43.1064	0.0144	0.0580	0.0040	0.0020	0.0062	0.0052
I8	2.6616	0.0272	0.3676	0.0015	0.4168	0.9300	0.0988	0.0036	0.0030	53.0940	0.0102	0.0500	0.0060	0.0020	0.0010	0.0010
I9	2.5000	0.0312	0.2714	0.0022	0.2398	1.0926	0.0908	0.0036	0.0030	46.5048	0.0104	0.0446	0.0044	0.0020	0.0010	0.0010
I10	2.8240	0.0214	0.3452	0.0036	0.2678	1.3652	0.1002	0.0040	0.0030	46.3760	0.0118	0.0348	0.0040	0.0020	0.0010	0.0010
J1	2.5912	0.0346	0.4034	0.0038	0.2852	1.3252	0.0890	0.0040	0.0088	47.0634	0.0116	0.0464	0.0056	0.0020	0.0010	0.0010
J2	2.9396	0.0312	0.3998	0.0032	0.2384	1.3726	0.0862	0.0040	0.0064	49.0722	0.0122	0.0414	0.0042	0.0020	0.0010	0.0010
J3	3.1694	0.0386	0.5410	0.0039	0.3910	1.4738	0.1240	0.0046	0.0240	46.9250	0.0136	0.0632	0.0068	0.0020	0.0010	0.0012
J4	2.8756	0.0308	0.3672	0.0046	0.2760	1.2370	0.0880	0.0038	0.0068	48.2860	0.0118	0.0426	0.0048	0.0020	0.0010	0.0010
J5	2.9448	0.0278	0.3786	0.0032	0.2356	1.3602	0.1070	0.0040	0.0176	48.5884	0.0114	0.0446	0.0050	0.0020	0.0010	0.0010
J6	3.1142	0.0336	0.5490	0.0028	0.3460	1.3112	0.1052	0.0038	0.0434	47.4862	0.0106	0.0582	0.0066	0.0020	0.0066	0.0010
J7	2.8792	0.0362	0.4474	0.0038	0.4526	1.3096	0.1096	0.0040	0.0402	48.1402	0.0102	0.0520	0.0058	0.0020	0.0056	0.0014
J8	2.9700	0.0218	0.2928	0.0015	0.3046	1.0978	0.0818	0.0034	0.0030	56.9778	0.0110	0.0600	0.0090	0.0020	0.0010	0.0010
J9	3.1092	0.0328	0.3484	0.0048	0.2668	1.4288	0.0894	0.0040	0.0030	50.1494	0.0118	0.0396	0.0054	0.0020	0.0010	0.0010
J10	3.2000	0.0352	0.4332	0.0026	0.2782	1.2398	0.1160	0.0038	0.0030	50.2032	0.0114	0.0428	0.0060	0.0020	0.0010	0.0010
K1	2.9472	0.0346	0.3496	0.0038	0.2788	1.4660	0.0800	0.0038	0.0064	47.9574	0.0116	0.0414	0.0056	0.0020	0.0012	0.0010
K2	3.0918	0.0380	0.3962	0.0037	0.2764	1.5498	0.1074	0.0046	0.0180	48.3438	0.0112	0.0520	0.0054	0.0020	0.0010	0.0012
K3	2.9566	0.0326	0.4598	0.0102	0.4062	1.2930	0.0958	0.0040	0.0126	44.7362	0.0124	0.0312	0.0048	0.0020	0.0010	0.0010
K4	3.0224	0.0348	0.3448	0.0036	0.1986	1.3760	0.0884	0.0038	0.0132	48.8536	0.0112	0.0330	0.0046	0.0020	0.0048	0.0010
K5	3.3110	0.0316	0.8186	0.0068	0.3964	1.4896	0.1450	0.0044	0.0462	44.3896	0.0130	0.0570	0.0052	0.0020	0.0044	0.0010
K6	2.7784	0.0362	0.3220	0.0084	0.2588	1.1540	0.0672	0.0034	0.0030	51.6034	0.0112	0.0316	0.0040	0.0020	0.0010	0.0010
K7	2.9190	0.0340	0.5376	0.0043	0.3360	1.2552	0.1676	0.0042	0.0264	48.5890	0.0118	0.0574	0.0048	0.0020	0.0012	0.0010
K8	2.6124	0.0288	0.3368	0.0033	0.2414	1.2748	0.0778	0.0044	0.0030	45.2764	0.0110	0.0388	0.0048	0.0020	0.0010	0.0010
K9	2.9716	0.0288	0.7702	0.0041	0.3844	1.3616	0.1722	0.0040	0.0378	45.0100	0.0100	0.0658	0.0062	0.0020	0.0024	0.0014
K10	3.1202	0.0368	0.4956	0.0043	0.3506	1.2874	0.1044	0.0040	0.0352	48.5550	0.0114	0.0504	0.0070	0.0020	0.0026	0.0010
L1	2.7290	0.0330	0.3790	0.0031	0.2230	1.1860	0.0736	0.0038	0.0050	48.8714	0.0114	0.0432	0.0054	0.0020	0.0010	0.0010
L2	2.4484	0.0202	0.3224	0.0015	0.2342	0.9774	0.0692	0.0038	0.0030	51.0650	0.0114	0.0368	0.0054	0.0020	0.0010	0.0010
L3	2.6868	0.0370	0.3618	0.0026	0.2430	1.2224	0.0756	0.0040	0.0030	48.3786	0.0116	0.0368	0.0056	0.0020	0.0010	0.0010
L4	3.3000	0.0356	0.4110	0.0032	0.2310	1.5196	0.0968	0.0042	0.0060	48.9048	0.0122	0.0330	0.0048	0.0020	0.0010	0.0010
L5	3.0364	0.0354	0.8958	0.0033	0.3568	1.3170	0.2186	0.0044	0.0518	45.4178	0.0132	0.0674	0.0048	0.0020	0.0026	0.0014
L6	2.8568	0.0346	0.6254	0.0062	0.3068	1.2776	0.1744	0.0040	0.0356	47.5466	0.0132	0.0456	0.0062	0.0020	0.0010	0.0010

L7	3.0114	0.0280	0.4270	0.0042	0.3126	1.3894	0.1252	0.0036	0.0134	47.7994	0.0118	0.0554	0.0064	0.0020	0.0010	0.0010
L8	3.1380	0.0330	0.7216	0.0062	0.3352	1.2364	0.1716	0.0040	0.0612	46.5266	0.0110	0.0560	0.0074	0.0020	0.0010	0.0010
L9	2.7844	0.0290	0.5690	0.0062	0.3424	1.3310	0.1098	0.0036	0.0184	49.0534	0.0110	0.0724	0.0062	0.0020	0.0012	0.0010
L10	3.1656	0.0294	0.5004	0.0038	0.3354	1.4500	0.1000	0.0040	0.0220	49.1208	0.0106	0.0692	0.0098	0.0020	0.0020	0.0010
M1	3.1372	0.0352	0.3910	0.0048	0.2718	1.4940	0.0674	0.0032	0.0030	51.3460	0.0120	0.0364	0.0050	0.0020	0.0010	0.0010
M2	2.9116	0.0304	0.5652	0.0046	0.3510	1.2536	0.1024	0.0036	0.0346	48.0322	0.0122	0.0444	0.0064	0.0020	0.0032	0.0024
M3	2.9248	0.0264	0.6066	0.0056	0.3182	1.2988	0.1048	0.0036	0.0208	46.6928	0.0118	0.0504	0.0070	0.0020	0.0010	0.0010
M4	2.4474	0.0288	0.3058	0.0028	0.2420	1.0926	0.0496	0.0036	0.0030	44.1806	0.0110	0.0368	0.0050	0.0020	0.0010	0.0010
M5	2.3590	0.0314	0.5464	0.0041	0.2782	0.9752	0.1068	0.0034	0.0214	41.0934	0.0112	0.0416	0.0056	0.0020	0.0010	0.0010
M6	2.4430	0.0342	0.5212	0.0046	0.3502	1.1288	0.0998	0.0040	0.0138	42.8944	0.0118	0.0396	0.0082	0.0020	0.0010	0.0010
M7	2.3468	0.0250	0.3002	0.0044	0.2386	1.0454	0.0484	0.0040	0.0030	44.5394	0.0112	0.0370	0.0050	0.0020	0.0010	0.0010
M8	2.5934	0.0298	0.4920	0.0048	0.2990	1.2028	0.0994	0.0036	0.0226	44.4462	0.0118	0.0416	0.0068	0.0020	0.0010	0.0010
M9	2.5784	0.0360	0.3860	0.0064	0.2876	1.2514	0.0824	0.0038	0.0030	45.7714	0.0124	0.0378	0.0046	0.0020	0.0010	0.0010
M10	2.8580	0.0378	0.3940	0.0040	0.2520	1.3974	0.0904	0.0040	0.0030	47.0734	0.0118	0.0368	0.0054	0.0020	0.0010	0.0024
N1	2.6450	0.0324	0.3308	0.0027	0.2646	1.2720	0.0718	0.0040	0.0030	48.1428	0.0114	0.0448	0.0054	0.0020	0.0010	0.0010
N2	2.6694	0.0348	0.3930	0.0032	0.2300	1.3294	0.0780	0.0044	0.0238	47.8528	0.0114	0.0348	0.0046	0.0020	0.0010	0.0010
N3	2.2736	0.0236	0.3110	0.0030	0.2496	1.1010	0.0542	0.0034	0.0030	46.8478	0.0112	0.0346	0.0044	0.0020	0.0010	0.0010
N4	2.8696	0.0346	0.4160	0.0038	0.2388	1.3624	0.0968	0.0036	0.0104	48.2064	0.0120	0.0436	0.0052	0.0020	0.0010	0.0010
N5	3.4388	0.0288	0.6962	0.0042	0.3482	1.5182	0.1364	0.0050	0.0344	46.7222	0.0140	0.0570	0.0058	0.0020	0.0010	0.0012
N6	3.3280	0.0318	0.6144	0.0044	0.3092	1.5822	0.1466	0.0038	0.0330	47.5138	0.0118	0.0434	0.0052	0.0020	0.0010	0.0010
N7	2.7446	0.0316	0.4518	0.0050	0.2958	1.4552	0.0812	0.0044	0.0040	49.2710	0.0110	0.0438	0.0096	0.0020	0.0010	0.0010
N8	2.6798	0.0326	0.3738	0.0045	0.2726	1.3140	0.0806	0.0042	0.0060	47.2078	0.0112	0.0318	0.0042	0.0020	0.0010	0.0010
N9	3.1870	0.0318	0.8590	0.0092	0.5094	1.2478	0.1732	0.0040	0.0478	46.6458	0.0122	0.0652	0.0062	0.0020	0.0026	0.0012
N10	2.9604	0.0358	0.3566	0.0050	0.2864	1.3792	0.0950	0.0040	0.0030	51.2040	0.0120	0.0438	0.0058	0.0020	0.0010	0.0010

Statistics	**Al**	**Ba**	**Ca**	**Cr**	**Fe**	**K**	**P**	**Rb**	**S**	**Si**	**Sr**	**Ti**	**Zr**	**Cl***	**Pb***	**Zn***
Mean	2.9704	0.0319	0.6768	0.0046	0.3445	1.2758	0.1373	0.0040	0.0352	45.8946	0.0122	0.0531	0.0057	0.0033	0.0015	0.0013
Median	2.9604	0.0326	0.5410	0.0042	0.3280	1.2716	0.1170	0.0040	0.0238	46.6760	0.0118	0.0500	0.0054	0.0020	0.0010	0.0010
SE	0.0289	0.0004	0.0449	0.0002	0.0087	0.0118	0.0057	0.0000	0.0032	0.3136	0.0001	0.0015	0.0001	0.0005	0.0001	0.0001
SD	0.3306	0.0046	0.5135	0.0019	0.0995	0.1352	0.0654	0.0003	0.0372	3.5890	0.0014	0.0171	0.0012	0.0052	0.0013	0.0010
Max	4.1800	0.0412	4.1180	0.0140	0.7316	1.7204	0.4216	0.0054	0.2248	56.9778	0.0184	0.1302	0.0098	0.0378	0.0090	0.0068
Min	2.0072	0.0182	0.2714	0.0015	0.1986	0.9300	0.0484	0.0032	0.0030	33.1684	0.0100	0.0312	0.0040	0.0020	0.0010	0.0010

Sheet 4: Correlations

		pH	EC	LOI	MagSus	Al	Ba	Ca	Cr	Fe	K	P	Rb	S	Si	Sr	Ti	Zr
pH	Pearson Correlation	1	-.776**	-.483**	-.429**	-.246**	-0.079	-.291**	-.389**	-.436**	-0.037	-.381**	-0.149	-.500**	.341**	-.234**	-.430**	-.184*
	Sig. (2-tailed)		0.000	0.000	0.000	0.005	0.369	0.001	0.000	0.000	0.673	0.000	0.089	0.000	0.000	0.007	0.000	0.036
EC	Pearson Correlation	-.776**	1	.670**	.588**	.271**	0.057	.402**	.357**	.620**	-0.025	.393**	.178*	.714**	-.468**	.315**	.560**	.263**
	Sig. (2-tailed)	0.000		0.000	0.000	0.002	0.516	0.000	0.000	0.000	0.774	0.000	0.042	0.000	0.000	0.000	0.000	0.002
LOI	Pearson Correlation	-.483**	.670**	1	.823**	.291**	0.157	.814**	.429**	.820**	-0.084	.671**	.313**	.867**	-.716**	.690**	.786**	.437**
	Sig. (2-tailed)	0.000	0.000		0.000	0.001	0.074	0.000	0.000	0.000	0.339	0.000	0.000	0.000	0.000	0.000	0.000	0.000
MagSus	Pearson Correlation	-.429**	.588**	.823**	1	.294**	0.112	.617**	.308**	.753**	-0.012	.572**	.317**	.630**	-.590**	.611**	.725**	.328**
	Sig. (2-tailed)	0.000	0.000	0.000		0.001	0.202	0.000	0.000	0.000	0.888	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	Pearson Correlation	-.246**	.271**	.291**	.294**	1	.326**	.320**	.273**	.343**	.616**	.457**	.315**	.368**	0.089	.334**	.475**	0.052
	Sig. (2-tailed)	0.005	0.002	0.001	0.001		0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.314	0.000	0.000	0.553
Ba	Pearson Correlation	-0.079	0.057	0.157	0.112	.326**	1	0.158	0.155	0.145	.319**	.229**	0.167	0.120	-0.088	.217*	0.163	0.005
	Sig. (2-tailed)	0.369	0.516	0.074	0.202	0.000		0.072	0.078	0.098	0.000	0.009	0.057	0.171	0.317	0.013	0.062	0.957
Ca	Pearson Correlation	-.291**	.402**	.814**	.617**	.320**	0.158	1	.442**	.767**	-0.092	.784**	.326**	.772**	-.672**	.734**	.721**	.378**
	Sig. (2-tailed)	0.001	0.000	0.000	0.000	0.000	0.072		0.000	0.000	0.298	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Cr	Pearson Correlation	-.389**	.357**	.429**	.308**	.273**	0.155	.442**	1	.422**	0.125	.335**	.180*	.390**	-.363**	.399**	.254**	0.121
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.002	0.078	0.000		0.000	0.156	0.000	0.039	0.000	0.000	0.000	0.003	0.170
Fe	Pearson Correlation	-.436**	.620**	.820**	.753**	.343**	0.145	.767**	.422**	1	-0.065	.650**	.298**	.789**	-.591**	.636**	.767**	.373**
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.098	0.000	0.000		0.460	0.000	0.001	0.000	0.000	0.000	0.000	0.000
K	Pearson Correlation	-0.037	-0.025	-0.084	-0.012	.616**	.319**	-0.092	0.125	-0.065	1	0.015	.453**	-0.057	.291**	0.063	0.075	-0.075
	Sig. (2-tailed)	0.673	0.774	0.339	0.888	0.000	0.000	0.298	0.156	0.460		0.861	0.000	0.519	0.001	0.475	0.392	0.393
P	Pearson Correlation	-.381**	.393**	.671**	.572**	.457**	.229**	.784**	.335**	.650**	0.015	1	.276**	.655**	-.526**	.597**	.667**	.214*
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.009	0.000	0.000	0.000	0.861		0.001	0.000	0.000	0.000	0.000	0.014
Rb	Pearson Correlation	-0.149	.178*	.313**	.317**	.315**	0.167	.326**	.180*	.298**	.453**	.276**	1	.283**	-.208*	.323**	.326**	0.107
	Sig. (2-tailed)	0.089	0.042	0.000	0.000	0.000	0.057	0.000	0.039	0.001	0.000	0.001		0.001	0.017	0.000	0.000	0.224
S	Pearson	-.500**	.714**	.867**	.630**	.368**	0.120	.772**	.390**	.789**	-0.057	.655**	.283**	1	-.628**	.621**	.707**	.315**

	Correlation																	
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.171	0.000	0.000	0.000	0.519	0.000	0.001		0.000	0.000	0.000	0.000
Si	Pearson Correlation	.341**	-.468**	-.716**	-.590**	0.089	-0.088	-.672**	-.363**	-.591**	.291**	-.526**	-.208*	-.628**	1	-.588**	-.464**	-.198*
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.314	0.317	0.000	0.000	0.000	0.001	0.000	0.017	0.000		0.000	0.000	0.023
Sr	Pearson Correlation	-.234**	.315**	.690**	.611**	.334**	.217*	.734**	.399**	.636**	0.063	.597**	.323**	.621**	-.588**	1	.591**	.194*
	Sig. (2-tailed)	0.007	0.000	0.000	0.000	0.000	0.013	0.000	0.000	0.000	0.475	0.000	0.000	0.000	0.000		0.000	0.026
Ti	Pearson Correlation	-.430**	.560**	.786**	.725**	.475**	0.163	.721**	.254**	.767**	0.075	.667**	.326**	.707**	-.464**	.591**	1	.430**
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	0.062	0.000	0.003	0.000	0.392	0.000	0.000	0.000	0.000	0.000		0.000
Zr	Pearson Correlation	-.184*	.263**	.437**	.328**	0.052	0.005	.378**	0.121	.373**	-0.075	.214*	0.107	.315**	-.198*	.194*	.430**	1
	Sig. (2-tailed)	0.036	0.002	0.000	0.000	0.553	0.957	0.000	0.170	0.000	0.393	0.014	0.224	0.000	0.023	0.026	0.000	

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Sheet 5: Grid coordinates and PCA results

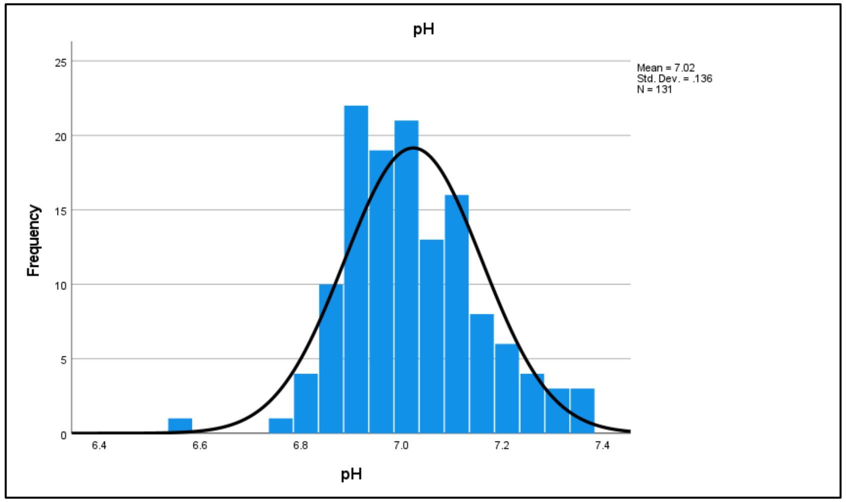
Grid	POINT X	POINT Y	PC1	PC2	PC3	PC4
A1	310866.6008	869145.4254	0.440	-1.012	0.761	-1.806
A2	310866.3707	869144.965	-2.169	-1.134	-0.541	-0.521
A3	310866.1246	869144.5205	0.592	-1.268	-0.761	-0.788
A4	310865.8706	869144.0681	-0.392	-0.113	-0.111	-1.125
A5	310865.6325	869143.6156	0.957	0.602	-0.153	-1.470
A6	310865.3943	869143.1553	1.185	0.384	0.115	-2.106
A7	310865.1483	869142.7108	-0.481	-0.564	-1.209	0.661
A8	310864.9022	869142.2663	0.963	0.319	0.503	-1.194
A9	310864.6641	869141.8059	0.170	3.040	-2.041	-2.145
A10	310864.4101	869141.3534	-0.180	1.656	-0.195	0.854
B1	310866.1802	869145.6556	2.661	0.636	-2.356	-0.317
B2	310865.9341	869145.2031	8.170	-2.466	1.190	-0.119
B3	310865.6801	869144.7507	-0.201	0.897	-0.561	-0.253
B4	310865.442	869144.2983	-0.583	0.125	-0.282	-0.704
B5	310865.1959	869143.8538	0.809	2.435	0.878	-0.913
B6	310864.9498	869143.4013	-1.589	-1.607	1.521	0.060
B7	310864.7038	869142.9489	1.345	0.468	0.969	-0.855
B8	310864.4577	869142.4964	0.705	0.809	-2.491	0.081
B9	310864.2117	869142.044	5.562	-2.928	-4.739	-0.502
B10	310863.9815	869141.5916	-0.941	-0.734	-0.787	-0.955
C1	310865.7357	869145.8937	1.519	0.597	-1.540	-0.506
C2	310865.4817	869145.4333	9.348	-1.577	1.771	0.725
C3	310865.2435	869144.9809	0.555	1.585	-0.574	-0.280
C4	310864.9975	869144.5364	1.949	1.043	-1.005	0.519
C5	310864.7593	869144.0919	-0.756	2.038	-0.387	-0.671
C6	310864.5053	869143.6394	0.274	-0.753	-1.089	-0.381
C7	310864.2672	869143.187	-1.266	2.825	-0.151	-0.778
C8	310864.0212	869142.7266	4.310	-1.314	-1.974	0.444
C9	310863.7751	869142.2821	-1.057	0.622	-1.042	0.241
C10	310863.529	869141.8297	-3.014	-0.051	-1.118	1.518
D1	310865.2912	869146.1318	0.807	-2.211	-0.549	-0.814
D2	310865.0451	869145.6794	-0.097	-3.423	0.503	-0.185
D3	310864.799	869145.219	-0.241	-1.317	0.254	-0.896
D4	310864.5609	869144.7745	5.628	-1.338	-0.395	-0.278
D5	310864.3148	869144.3221	0.843	-2.505	-1.368	0.515
D6	310864.0688	869143.8696	1.744	-2.499	-1.161	0.684

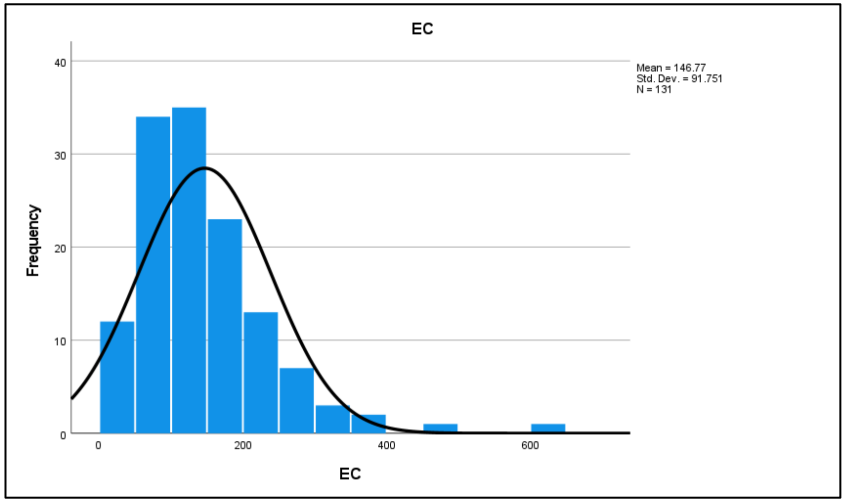
D7	310863.8227	869143.4251	0.486	-1.346	-1.213	-0.466
D8	310863.5767	869142.9727	-0.866	-0.183	-0.660	-0.092
D9	310863.3385	869142.5123	-0.989	-0.132	-0.466	0.985
D10	310863.0925	869142.0678	-1.403	1.119	-0.236	-0.102
E1	310864.8863	869146.3382	2.057	-0.190	2.400	-0.067
E2	310864.6323	869145.8937	0.814	-0.762	-0.317	-1.554
E3	310864.3942	869145.4413	0.997	-0.034	0.027	0.053
E4	310864.1402	869144.9968	7.258	4.006	-0.160	2.137
E5	310863.8862	869144.5443	3.293	-0.090	-0.990	-0.418
E6	310863.6402	869144.0998	2.976	1.971	-0.708	1.234
E7	310863.3941	869143.6394	-1.705	1.046	-0.763	0.029
E8	310863.1322	869143.1949	-2.319	-0.937	-0.187	0.036
E9	310862.894	869142.7425	-1.914	-0.343	-0.447	0.182
E10	310862.648	869142.3059	-1.418	0.698	-1.104	-0.608
F1	310864.4418	869146.5843	0.442	0.737	0.666	-0.116
F2	310864.1958	869146.1239	1.819	-0.154	-0.251	-0.061
F3	310863.9418	869145.6794	2.390	0.028	0.237	-2.090
F4	310863.6878	869145.2428	12.589	-1.904	0.742	1.574
F5	310863.4417	869144.7904	6.182	0.001	0.717	0.088
F6	310863.1877	869144.3459	4.022	1.135	1.351	-0.446
F7	310862.9417	869143.8934	0.251	-0.332	-0.593	-0.362
F8	310862.6877	869143.441	2.386	2.116	0.841	-0.263
G1	310863.9973	869146.8303	0.822	0.859	1.100	-0.046
G9	310862.005	869143.2426	6.743	0.618	3.073	-0.396
G10	310861.751	869142.7901	9.199	-1.258	4.427	-0.695
H1	310863.5528	869147.0764	-1.328	-1.901	-0.211	1.236
H2	310863.2988	869146.6319	2.584	1.543	0.241	0.231
H3	310863.0607	869146.1794	2.244	0.909	-0.759	-0.971
H4	310862.8147	869145.727	-1.045	0.776	0.356	0.008
H5	310862.5607	869145.2904	-0.016	0.912	0.250	1.003
H6	310862.3067	869144.838	-0.502	1.390	1.104	0.844
H7	310862.0527	869144.3856	0.794	0.112	-0.185	1.765
H8	310861.8145	869143.9331	-0.395	-0.902	0.123	0.423
H9	310861.5605	869143.4886	0.639	0.384	-0.606	2.140
H10	310861.3145	869143.0521	-0.916	0.443	-0.144	0.809
I1	310867.0533	869145.1793	-1.790	0.503	0.673	0.752
I2	310866.7993	869144.7269	-2.306	-0.400	0.368	0.398
I3	310866.5612	869144.2824	-1.589	-1.709	-0.336	-1.249
I4	310866.3072	869143.8141	-2.463	-1.815	1.041	-0.608
I5	310866.077	869143.3696	-1.472	-0.297	0.812	-0.387

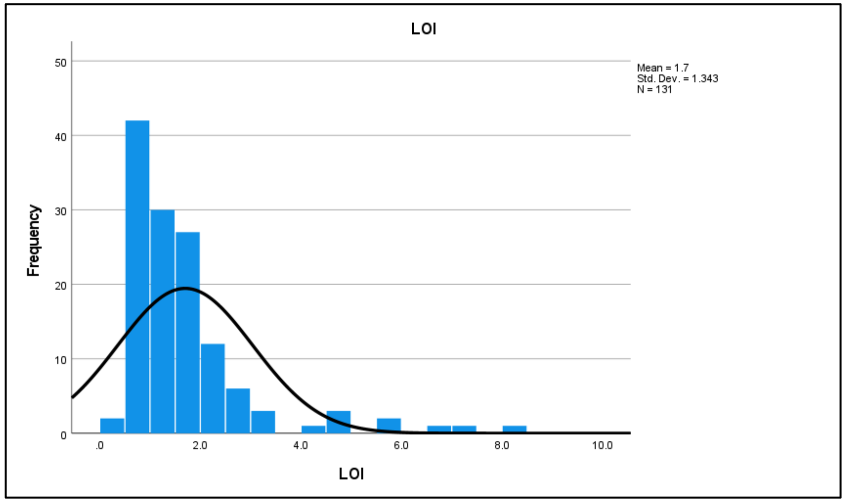
I6	310865.8309	869142.9251	-2.792	-3.888	1.096	0.711
I7	310865.5848	869142.4726	1.619	-0.980	0.852	-0.512
I8	310865.3467	869142.0202	-3.371	-2.209	1.366	1.823
I9	310865.1007	869141.5678	-3.592	-1.643	1.272	-0.217
I10	310864.8467	869141.1153	-2.981	-0.122	0.889	-0.167
J1	310867.4978	869144.9333	-1.791	0.069	0.123	-0.053
J2	310867.2517	869144.4888	-2.681	0.971	0.903	-0.270
J3	310867.0057	869144.0363	0.566	2.410	0.682	0.878
J4	310866.7517	869143.5839	-2.099	-0.123	-0.280	-0.576
J5	310866.5056	869143.1314	-2.110	0.474	-0.327	0.311
J6	310866.2754	869142.679	0.116	0.075	-2.081	1.112
J7	310866.0214	869142.2266	-0.248	0.298	-1.536	0.343
J8	310865.7833	869141.7741	-3.333	-1.472	0.467	4.202
J9	310865.5452	869141.3217	-2.733	1.661	1.337	0.220
J10	310865.2912	869140.8772	-2.345	0.727	0.526	0.647
K1	310867.9264	869144.7031	-2.295	1.184	0.454	0.131
K2	310867.6921	869144.243	-1.274	2.871	0.258	0.396
K3	310867.4412	869143.7962	-0.192	0.329	-0.806	-2.383
K4	310867.1963	869143.3433	-2.844	1.095	0.115	-0.586
K5	310866.9454	869142.8965	1.182	1.881	0.902	-0.334
K6	310866.7128	869142.4497	-2.731	-0.195	-1.098	-2.429
K7	310866.4619	869141.9906	-0.208	0.562	-0.401	-0.281
K8	310866.2232	869141.5438	-2.958	-0.113	1.533	0.096
K9	310865.9783	869141.0848	0.619	-0.081	-1.347	0.982
K10	310865.7396	869140.6441	-0.843	0.767	0.720	0.966
L1	310868.3715	869144.4572	-2.898	-0.438	0.725	0.140
L2	310868.1267	869144.0104	-3.868	-2.682	0.820	1.274
L3	310867.8818	869143.5575	-2.726	0.075	0.745	-0.008
L4	310867.6492	869143.1107	-2.443	2.648	1.290	-0.041
L5	310867.3983	869142.6639	1.426	1.032	0.666	-0.225
L6	310867.1535	869142.2049	0.162	0.296	-0.148	-0.648
L7	310866.9025	869141.7642	-1.493	0.181	0.197	0.916
L8	310866.6577	869141.3051	1.056	-0.033	-1.723	0.450
L9	310866.4129	869140.8461	-0.652	-0.278	-1.026	0.528
L10	310866.1742	869140.3993	-0.580	0.825	-0.372	3.568
M1	310868.806	869144.2185	-3.147	1.458	1.001	-0.362
M2	310868.5673	869143.7717	-0.397	-0.661	-0.035	0.508
M3	310868.3286	869143.3188	-0.419	-0.798	-1.237	0.634
M4	310868.0838	869142.8659	-3.156	-2.209	0.334	-0.404
M5	310867.8267	869142.4191	-1.812	-3.225	0.952	-0.874

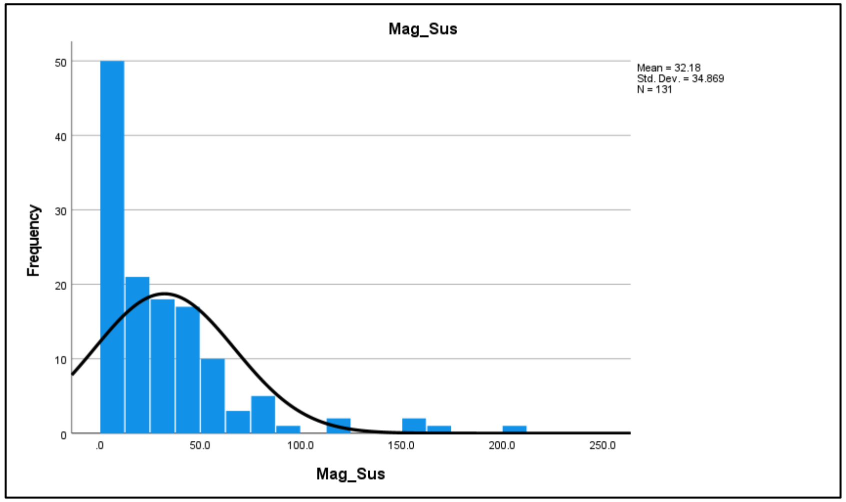
M6	310867.588	869141.9662	-0.636	-1.756	0.462	0.646
M7	310867.3432	869141.5132	-2.654	-2.405	0.062	-0.442
M8	310867.0984	869141.0603	-1.132	-1.627	-0.492	0.024
M9	310866.8475	869140.6135	-2.288	-0.140	1.220	-1.721
M10	310866.6088	869140.1606	-2.530	1.223	1.345	-0.394
N1	310869.2319	869144.0006	-2.823	-0.081	0.850	0.390
N2	310868.9896	869143.5514	-2.517	0.817	0.642	-0.414
N3	310868.7387	869143.0985	-3.659	-2.742	0.068	-0.444
N4	310868.5	869142.6333	-1.883	0.446	-0.783	-0.562
N5	310868.2613	869142.1865	1.257	2.675	-0.555	0.793
N6	310868.0226	869141.7336	-0.677	1.980	-0.826	-0.158
N7	310867.7839	869141.2868	-1.190	0.833	-0.432	2.517
N8	310867.5391	869140.8277	-2.837	0.464	1.011	-0.858
N9	310867.2881	869140.3748	2.198	0.210	-1.900	-0.766
N10	310867.05	869139.9276	-2.484	1.475	1.420	0.250

Sheet 6: Normality of geochemical and magnetic variables

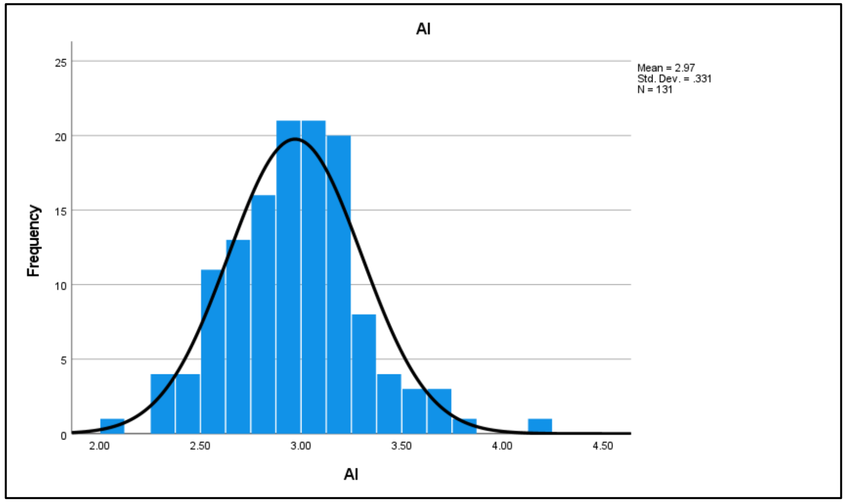


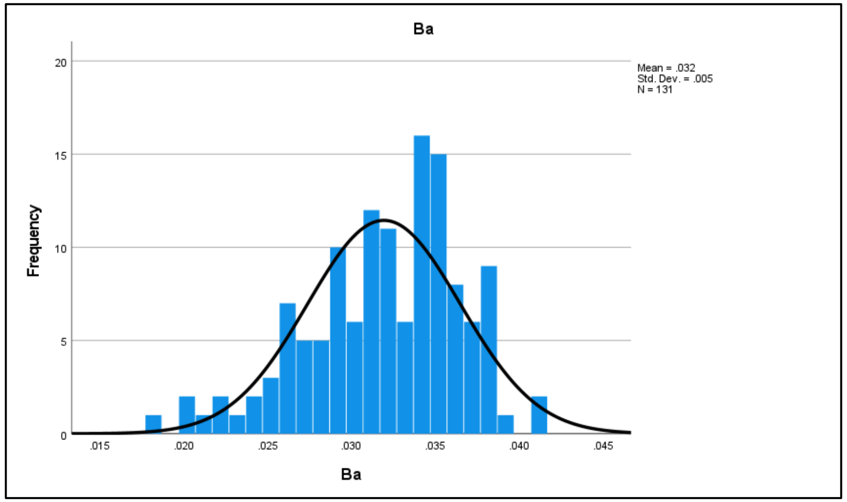


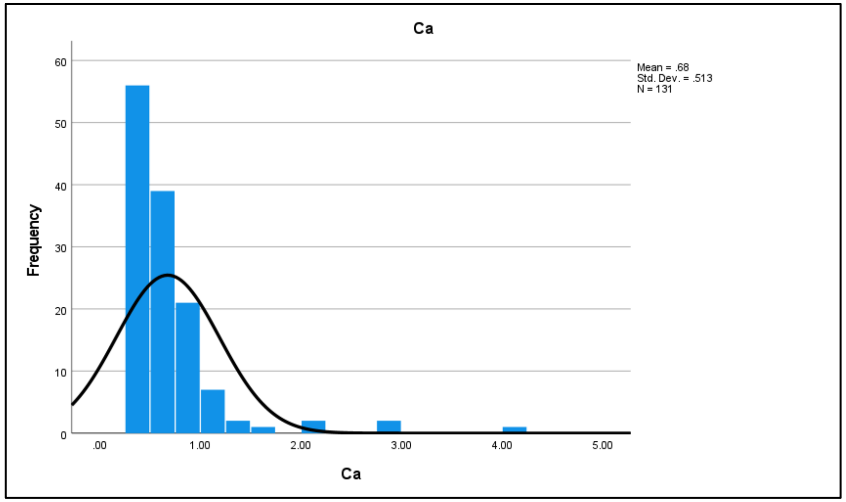


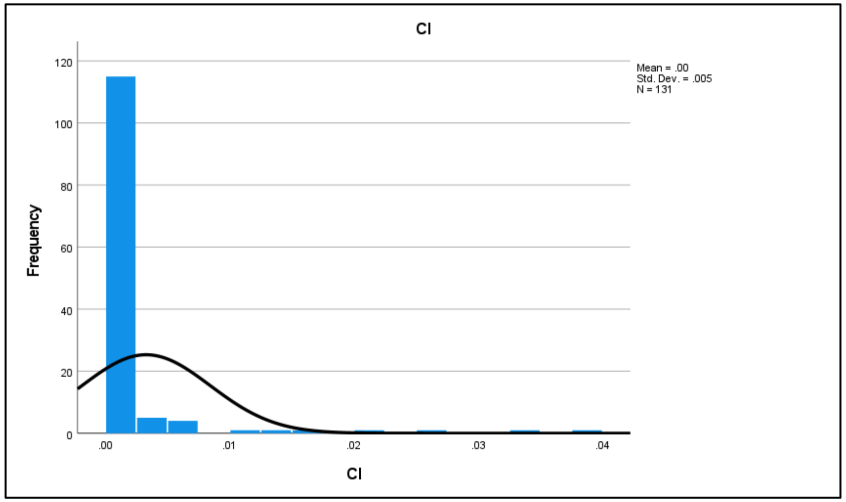


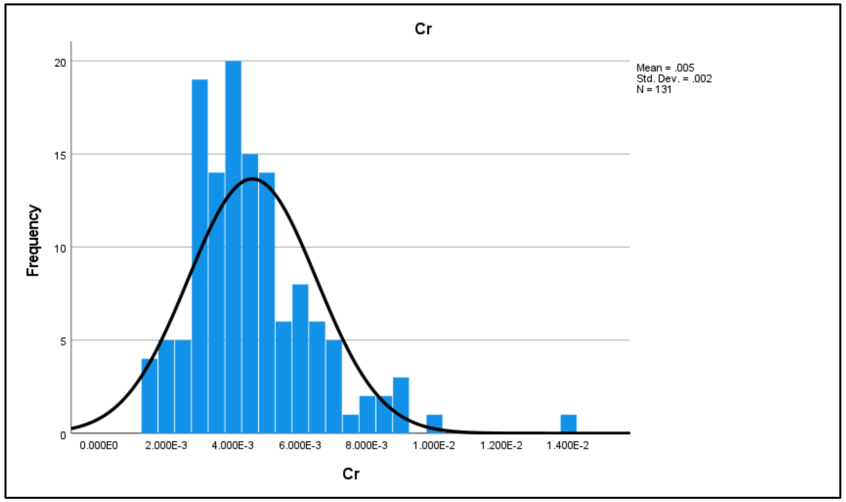
Sheet 6: Normality of multi-element variables










Cr
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Std. Dev. = .002
N = 131
Frequency
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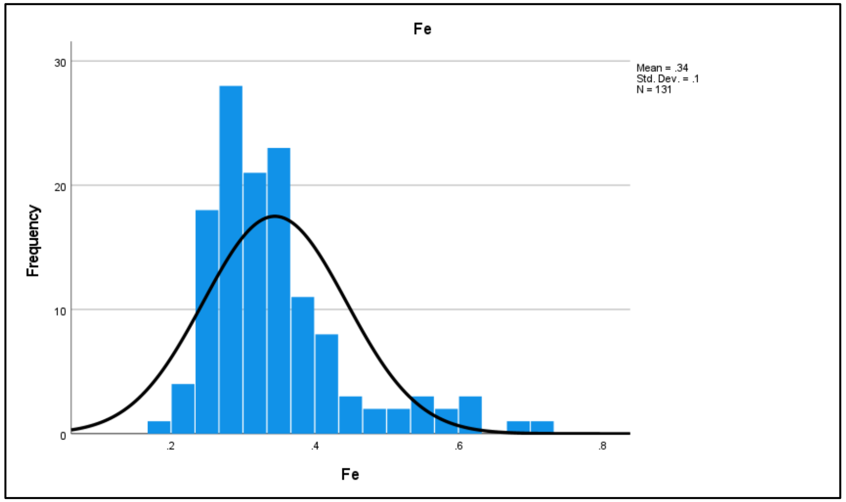
2.000E-3
4.000E-3
6.000E-3
8.000E-3
1.000E-2
1.200E-2
1.400E-2
Cr


Fe
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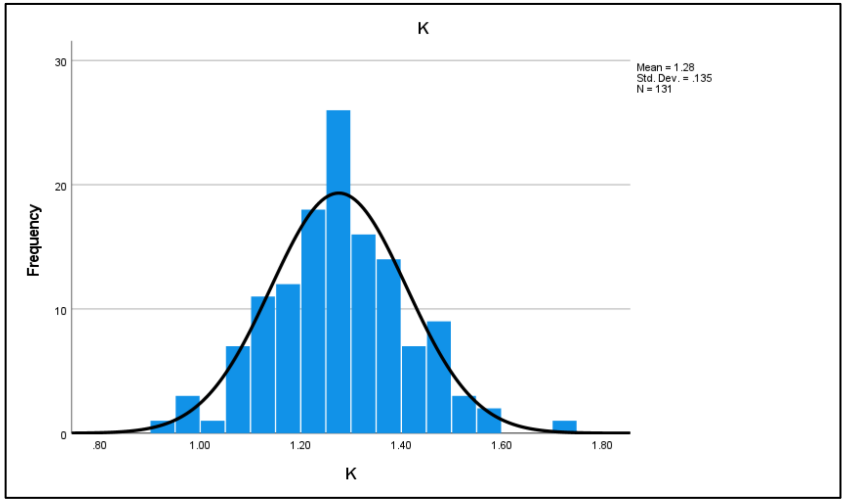
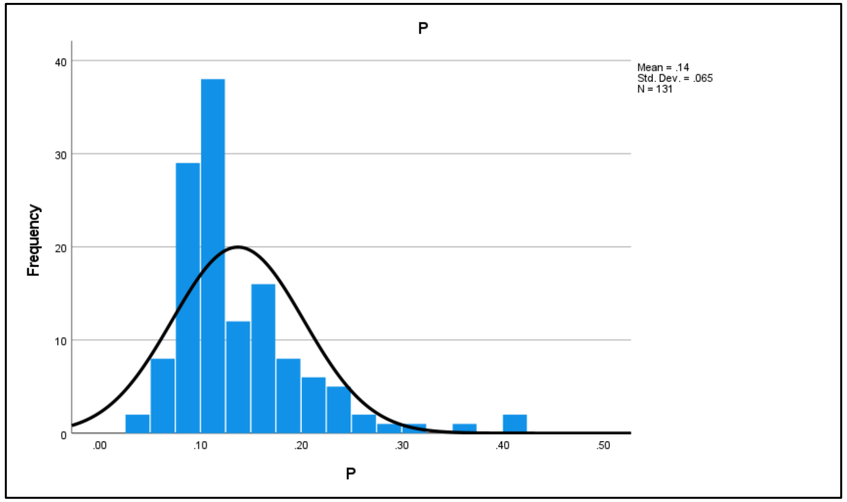
Std. Dev. = .1
N = 131
Frequency
Fe


K
Mean = 1.28
Std. Dev. = .135
N = 131
Frequency
K


P
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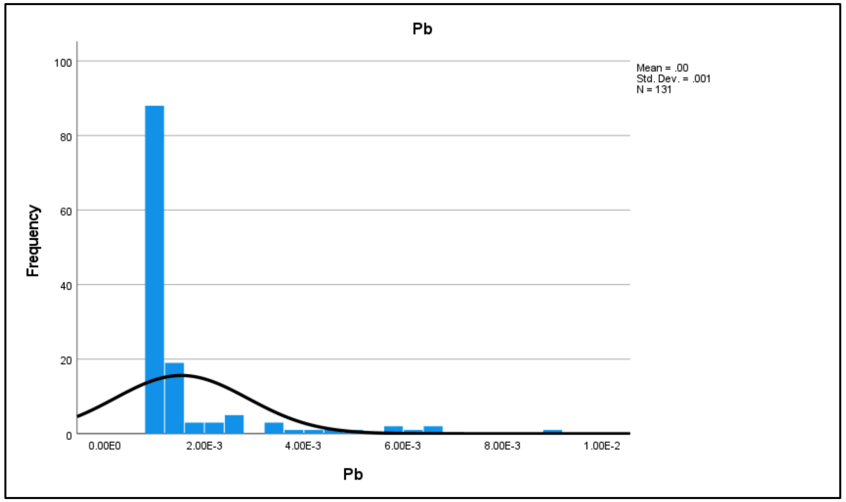
Frequency
P


Pb
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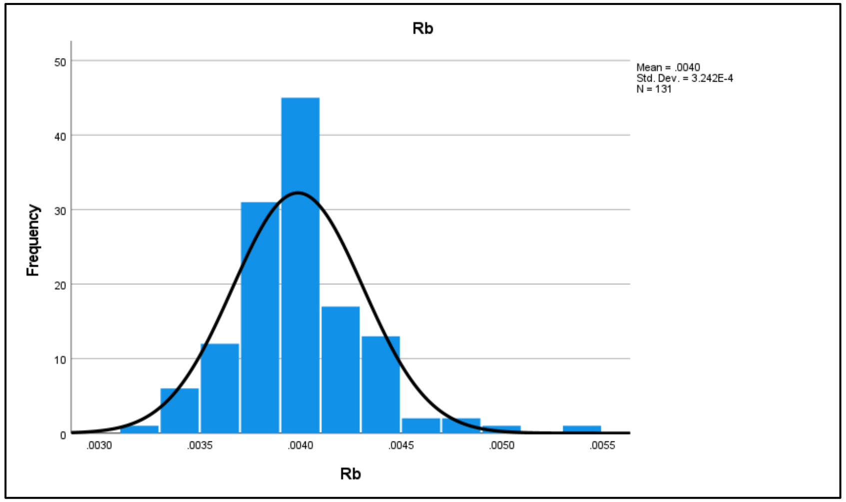
Std. Dev. = .001
N = 131
Frequency
Pb


Rb
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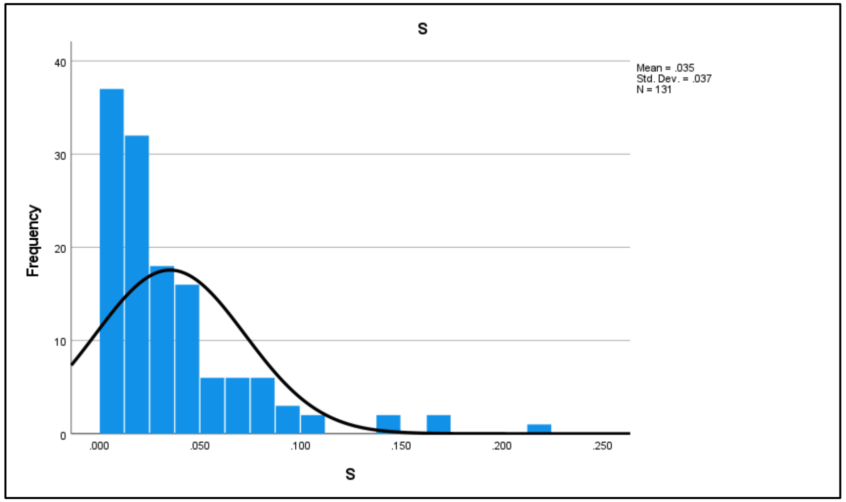
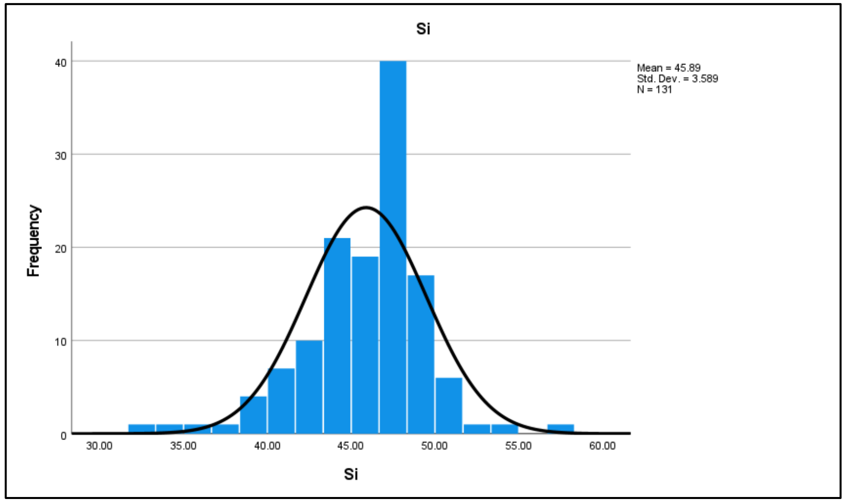
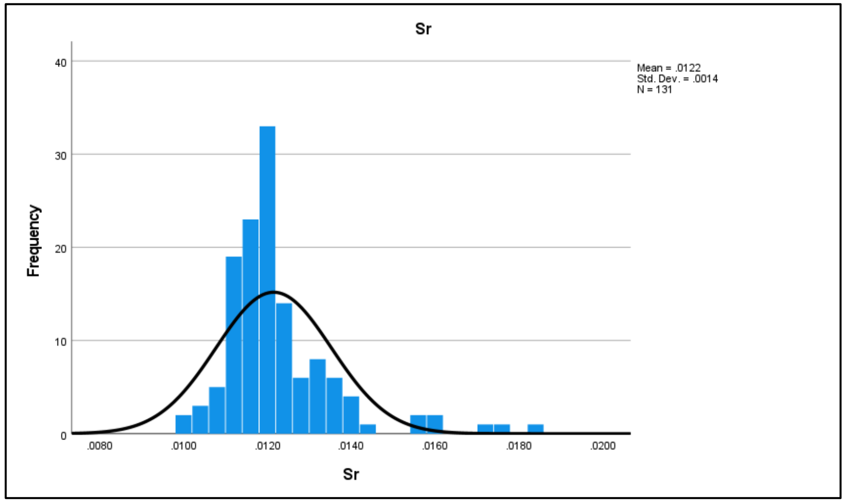
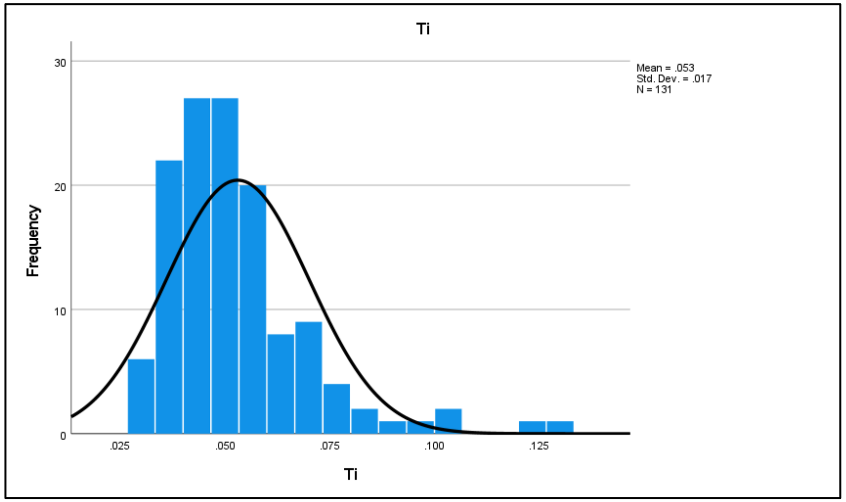
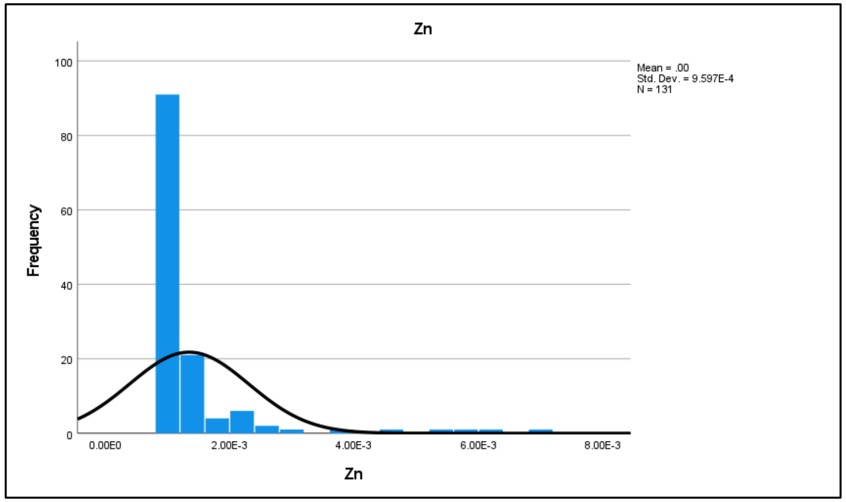
Std. Dev. = 3.242E-4
N = 131
Frequency
Rb

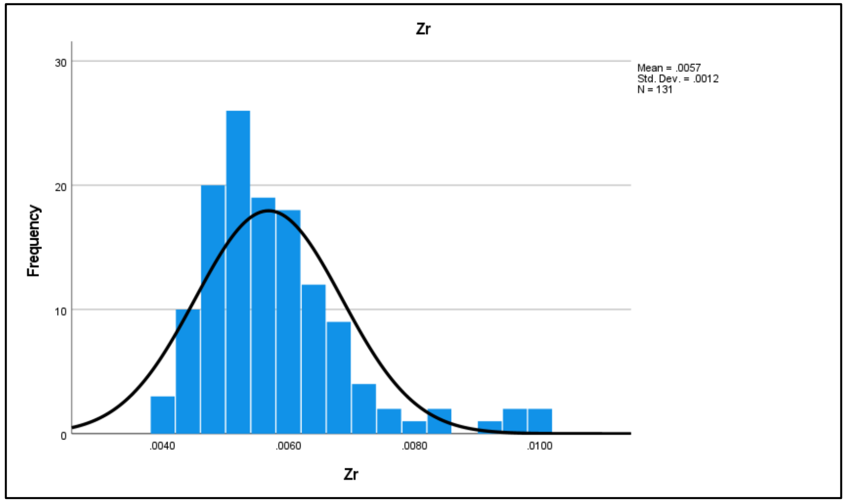

S
Mean = .035
Std. Dev. = .037
N = 131
Frequency
S


Si
Mean = 45.89
Std. Dev. = 3.589
N = 131
Frequency
Si

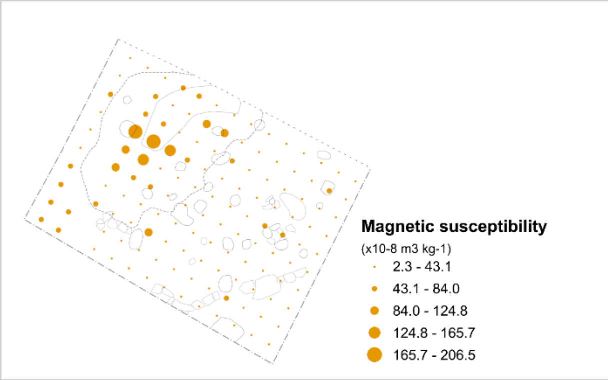

Sr
Mean = .0122
Std. Dev. = .0014
N = 131
Frequency
Sr


Ti
Mean = .053
Std. Dev. = .017
N = 131
Frequency
Ti

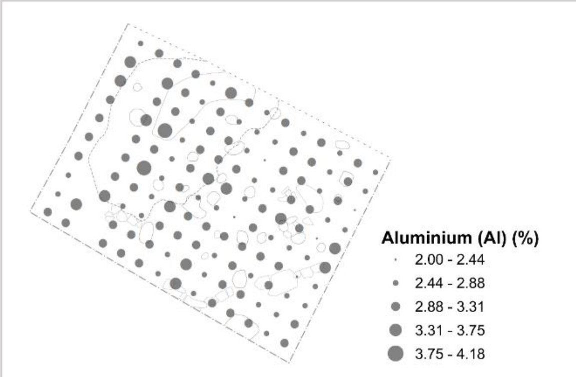

Zn
Mean = .00
Std. Dev. = 9.597E-4
N = 131
Frequency
Zn

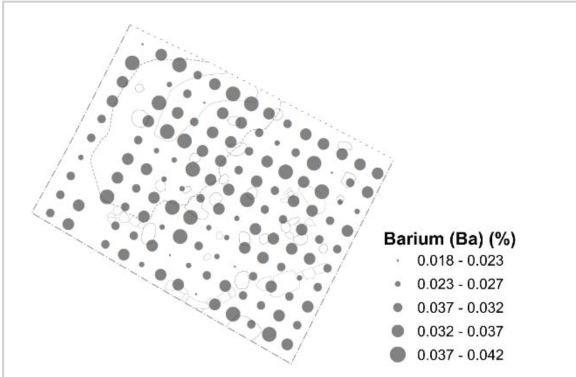

Zr
Mean = .0057
Std. Dev. = .0012
N = 131
Frequency
Zr

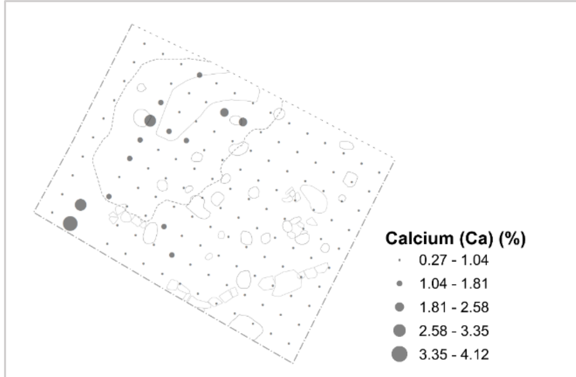
Sheet 8: Distribution of microrefuse, geochemical and magnetic variables

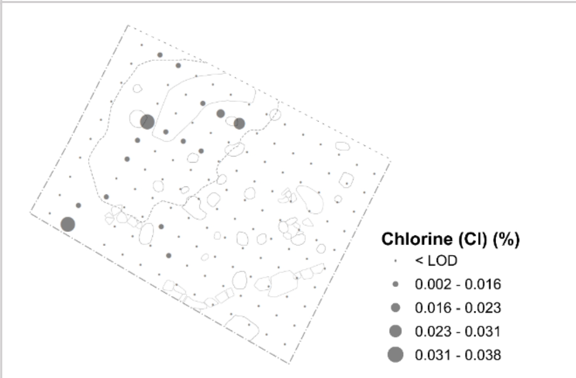

Magnetic susceptibility
(x10-8 m3 kg-1)
2.3 - 43.1
43.1 - 84.0
84.0 - 124.8
124.8 - 165.7
165.7 - 206.5

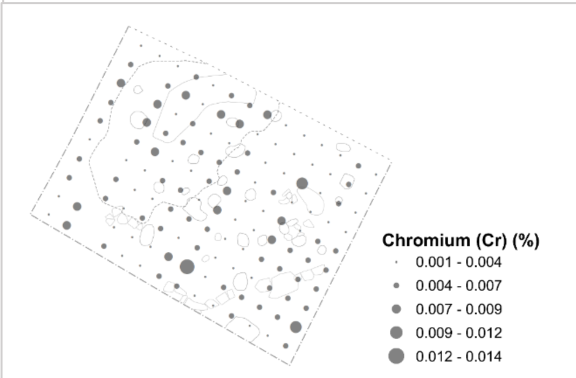
Sheet 9: Distribution of multi-element variables

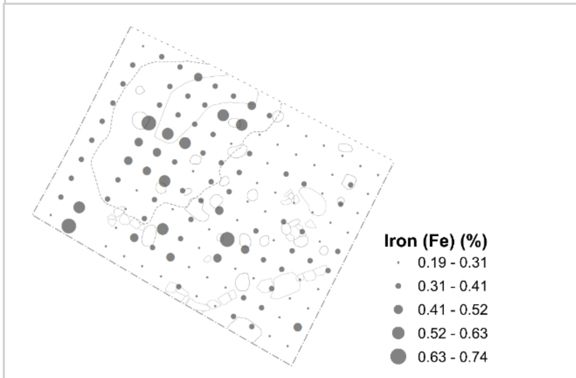


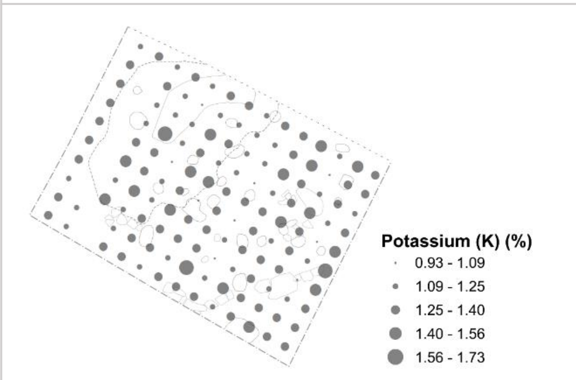


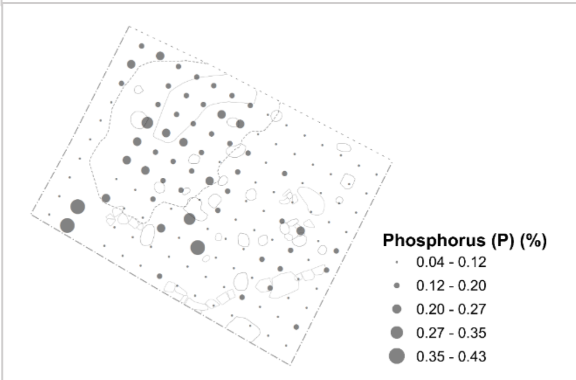


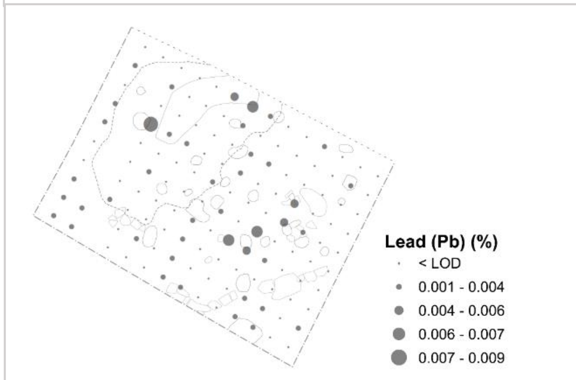


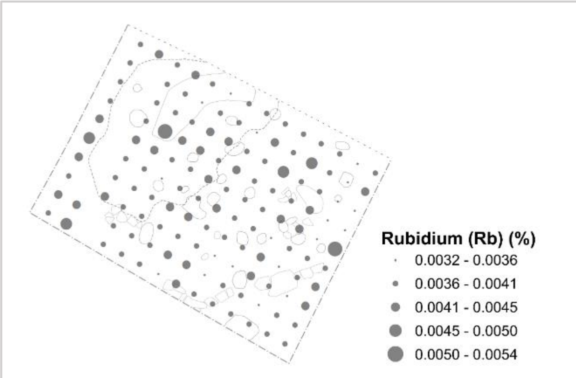


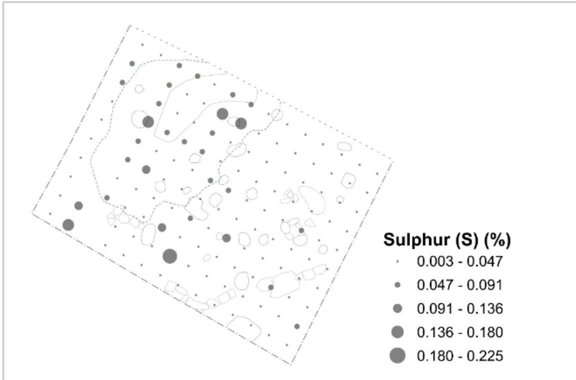


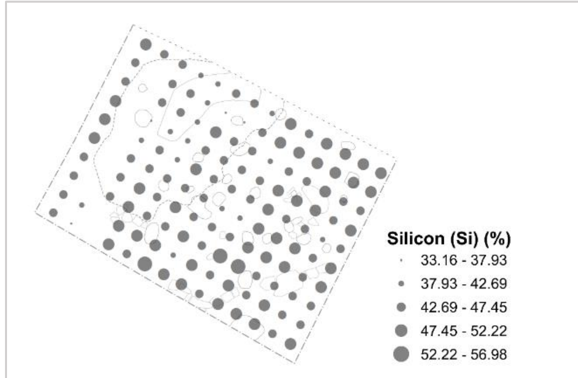


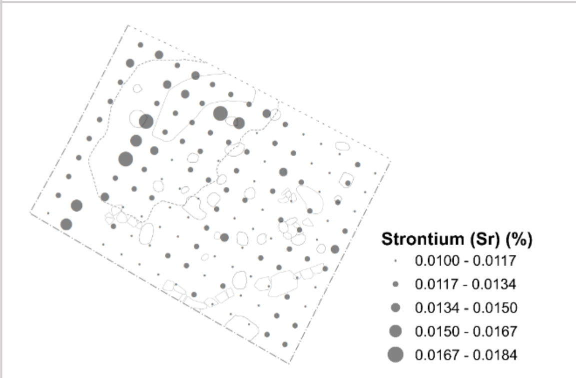


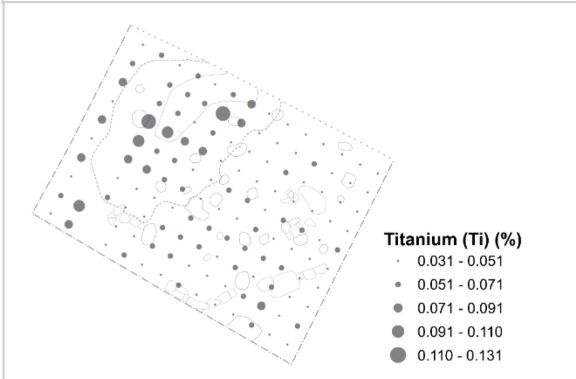


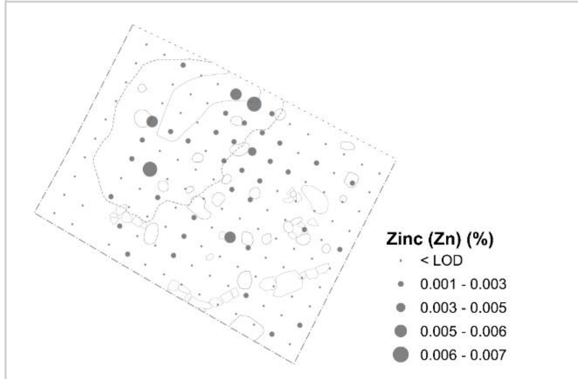

Rubidium (Rb) (%)
0.0032 - 0.0036
0.0036 - 0.0041
0.0041 - 0.0045
0.0045 - 0.0050
0.0050 - 0.0054

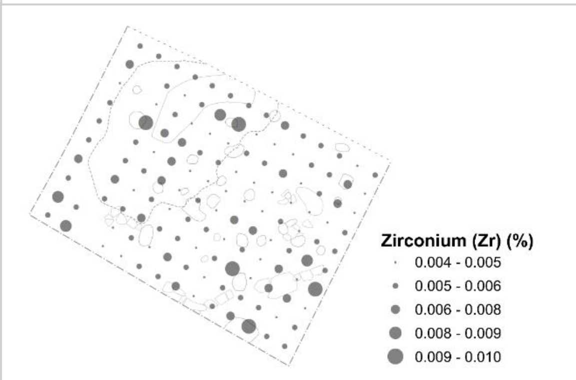

Sulphur (S) (%)
0.003 - 0.047
0.047 - 0.091
0.091 - 0.136
0.136 - 0.180
0.180 - 0.225


Silicon (Si) (%)
33.16 - 37.93
37.93 - 42.69
42.69 - 47.45
47.45 - 52.22
52.22 - 56.98


Strontium (Sr) (%)
0.0100 - 0.0117
0.0117 - 0.0134
0.0134 - 0.0150
0.0150 - 0.0167
0.0167 - 0.0184


Titanium (Ti) (%)
0.031 - 0.051
0.051 - 0.071
0.071 - 0.091
0.091 - 0.110
0.110 - 0.131


Zinc (Zn) (%)
< LOD
0.001 - 0.003
0.003 - 0.005
0.005 - 0.006
0.006 - 0.007


Zirconium (Zr) (%)
0.004 - 0.005
0.005 - 0.006
0.006 - 0.008
0.008 - 0.009
0.009 - 0.010

SM4: Microrefuse, geochemical, magnetic, multi-element and statistical data

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Sheet 1: Grid coordinates, geochemical, magnetic and microrefuse data

Grid	POINT_X	POINT_Y	pH	EC	LOI	Mag sus	Charcoal (2-30mm)	Burnt Bone (2-15mm)
A1	388238.8391	784657.2526	5.5	778	6.7	291.0	9	115
B1	388238.3628	784657.2407	5.1	557	6.5	160.7	15	3
C1	388237.8389	784657.2447	4.6	500	10.6	63.9	50	0
D1	388237.3428	784657.2368	4.5	438	7.6	71.8	39	0
A2	388238.9383	784656.697	4.8	792	7.7	207.5	40	0
B2	388238.4223	784656.6891	4.7	1543	7.0	155.0	9	11
C2	388237.8826	784656.6851	4.7	676	6.6	302.2	7	0
D2	388237.3905	784656.6891	4.7	520	7.1	65.5	44	0
A3	388238.974	784656.1255	5.0	569	5.8	141.5	27	1
B3	388238.4739	784656.1334	5.0	617	6.4	182.0	18	8
C3	388237.9381	784656.1374	4.7	645	4.9	83.7	15	0
D3	388237.4738	784656.1295	4.7	407	5.9	44.5	84	0
A4	388239.0137	784655.558	4.7	719	11.4	475.7	60	2
B4	388238.5057	784655.5659	4.9	288	7.7	79.5	53	0
C4	388237.9778	784655.5738	4.6	545	7.0	246.4	7	2
D4	388237.5214	784655.5659	4.8	382	4.4	85.2	15	0
A5	388239.0534	784655.0023	5.0	516	6.7	153.9	72	12
B5	388238.5454	784654.9944	4.6	486	7.0	1186.3	23	0
C5	388238.0215	784655.0023	4.4	398	10.9	910.9	56	0
D5	388237.5294	784654.9944	4.2	580	9.5	283.8	44	2
A6	388239.0216	784654.4308	4.9	247	6.9	113.4	44	0
B6	388238.5851	784654.4507	4.4	386	8.6	76.4	58	8
C6	388238.0771	784654.4666	4.2	623	13.0	1013.0	36	20
D6	388237.5889	784654.4705	4.6	312	11.4	578.2	190	3

Statistics	pH	EC	LOI	Mag sus	Charcoal (2-30mm)	Burnt Bone (2-15mm)
Mean	4.7	563.5	7.8	290.5	3	532
Median	4.7	532.5	7.0	157.8	4	394
SE	0.06	52.02	0.45	65.11	7.80	4.79
SD	0.29	254.85	2.21	318.98	38.22	23.48
Max	5.5	1543.0	13.0	1186.3	6	1543
Min	4.2	247.0	4.4	44.5	0	52

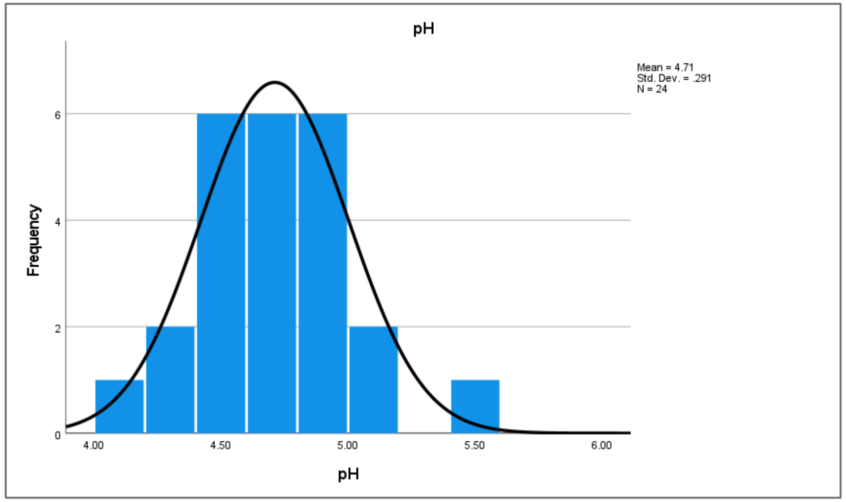
Sheet 2: Multi-element data

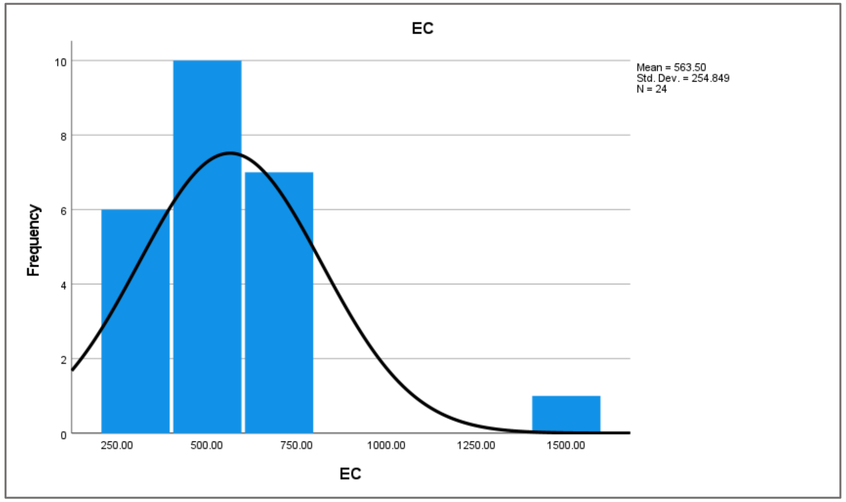
Grid	Al	Ba	Ca	Cl	Cr	Fe	K	Mn	P	Rb	S	Si	Sr	Ti	V[1]	Zn	Zr	Cu[2]*	Mg[3]*	Pb[4]*
1A	6.4066	0.0852	2.0652	0.0350	0.0146	3.0462	1.7322	0.3110	0.7764	0.0080	0.0674	25.6850	0.0288	0.5036	0.0086	0.0240	0.0168	0.0078	0.9786	0.0064
1B	7.1592	0.0734	1.0154	0.0604	0.0112	3.3522	1.8706	0.2048	0.4988	0.0084	0.0688	27.9098	0.0244	0.5518	0.0096	0.0134	0.0198	0.0031	1.0274	0.0026
1C	5.2768	0.0526	0.6058	0.0488	0.0110	2.4314	1.5564	0.0248	0.4848	0.0088	0.0936	25.7118	0.0152	0.5028	0.0074	0.0052	0.0210	0.0022	0.4934	0.0010
1D	6.4010	0.0650	0.7748	0.0490	0.0126	3.1270	1.7668	0.1026	0.5484	0.0088	0.0796	26.5354	0.0192	0.5044	0.0088	0.0090	0.0214	0.0073	0.8096	0.0018
2A	5.8080	0.0666	0.7480	0.0440	0.0108	2.9510	1.5430	0.1638	0.5282	0.0080	0.0744	25.3684	0.0198	0.4854	0.0088	0.0080	0.0192	0.0043	0.6888	0.0020
2B	6.0048	0.0900	2.3202	0.0390	0.0112	2.6006	1.6990	0.7224	0.7452	0.0082	0.0742	26.6088	0.0312	0.4894	0.0068	0.0486	0.0220	0.0045	0.5226	0.0016
2C	6.5046	0.0680	0.6908	0.0544	0.0108	2.6698	1.7002	0.1284	0.4746	0.0080	0.0558	28.0804	0.0174	0.5288	0.0096	0.0104	0.0216	0.0062	0.7992	0.0028
2D	6.2496	0.0688	0.8282	0.0498	0.0112	2.9882	1.6822	0.0782	0.6484	0.0082	0.0754	27.0646	0.0180	0.5290	0.0068	0.0080	0.0200	0.0020	0.6050	0.0018
3A	7.4156	0.0752	0.9436	0.0176	0.0156	3.2866	1.8914	0.2340	0.5532	0.0084	0.0682	29.2112	0.0212	0.5400	0.0116	0.0110	0.0198	0.0032	0.7806	0.0022
3B	6.6870	0.1002	2.0198	0.0282	0.0126	2.6392	1.6688	1.1096	0.7552	0.0078	0.0734	27.7224	0.0278	0.4942	0.0074	0.0388	0.0218	0.0062	0.6254	0.0022
3C	6.6538	0.0652	0.7088	0.0456	0.0122	2.6458	1.7912	0.1330	0.4466	0.0088	0.0492	31.1338	0.0164	0.5514	0.0076	0.0094	0.0210	0.0015	0.6360	0.0014
3D	6.8110	0.0676	0.7296	0.0210	0.0124	2.7006	1.8642	0.0584	0.4862	0.0088	0.0554	29.9210	0.0178	0.5228	0.0092	0.0078	0.0212	0.0015	0.7810	0.0020
4A	6.3022	0.0784	0.9784	0.0438	0.0120	3.1458	1.5466	0.3104	0.8652	0.0092	0.1134	25.9672	0.0184	0.4904	0.0072	0.0100	0.0192	0.0098	0.6806	0.0022
4B	6.6878	0.0752	0.8220	0.0230	0.0120	2.9158	1.7136	0.2162	0.6048	0.0088	0.0780	28.1488	0.0186	0.5016	0.0072	0.0066	0.0206	0.0023	0.7016	0.0012
4C	7.0440	0.0778	0.9800	0.0396	0.0130	2.9080	1.7926	0.2400	0.4774	0.0080	0.0592	28.5466	0.0198	0.5200	0.0084	0.0180	0.0206	0.0032	0.7176	0.0030
4D	7.5148	0.0570	0.7850	0.0292	0.0106	2.7356	1.9114	0.0766	0.3978	0.0086	0.0414	31.2102	0.0200	0.5422	0.0090	0.0086	0.0190	0.0015	0.9314	0.0014
5A	6.8298	0.0672	0.9862	0.0406	0.0122	3.1120	1.7738	0.2148	0.5436	0.0086	0.0626	27.5844	0.0200	0.5126	0.0110	0.0092	0.0198	0.0021	0.5866	0.0020
5B	6.9026	0.0940	0.9968	0.0764	0.0108	3.7580	1.6816	0.6506	1.1188	0.0084	0.0874	27.1418	0.0222	0.4874	0.0112	0.0156	0.0214	0.0030	0.6272	0.0014
5C	6.2744	0.0804	0.8044	0.0524	0.0118	3.5628	1.6066	0.2980	0.8744	0.0088	0.0962	24.1938	0.0178	0.4746	0.0096	0.0130	0.0194	0.0031	0.5082	0.0012
5D	6.9886	0.0728	0.8008	0.0818	0.0124	3.2282	1.7372	0.1830	0.7568	0.0090	0.1082	25.2732	0.0196	0.5112	0.0120	0.0090	0.0194	0.0042	0.5990	0.0112
6A	7.2628	0.0524	0.8122	0.0286	0.0116	3.1894	1.7722	0.0984	0.5394	0.0084	0.0858	28.6644	0.0212	0.5234	0.0094	0.0064	0.0198	0.0015	0.6296	0.0016
6B	6.4506	0.0660	0.5994	0.0464	0.0114	2.7964	1.5916	0.0872	0.5438	0.0086	0.0912	28.3330	0.0166	0.5148	0.0068	0.0048	0.0192	0.0022	0.6780	0.0020
6C	6.3150	0.0820	0.6344	0.0984	0.0136	3.8802	1.4520	0.7032	0.7824	0.0086	0.1294	22.8672	0.0166	0.4698	0.0102	0.0108	0.0204	0.0068	0.5320	0.0014
6D	6.8458	0.0568	0.6462	0.0580	0.0132	3.6866	1.5960	0.2048	0.6494	0.0090	0.1510	25.4062	0.0176	0.4750	0.0104	0.0076	0.0214	0.0029	0.6344	0.0010

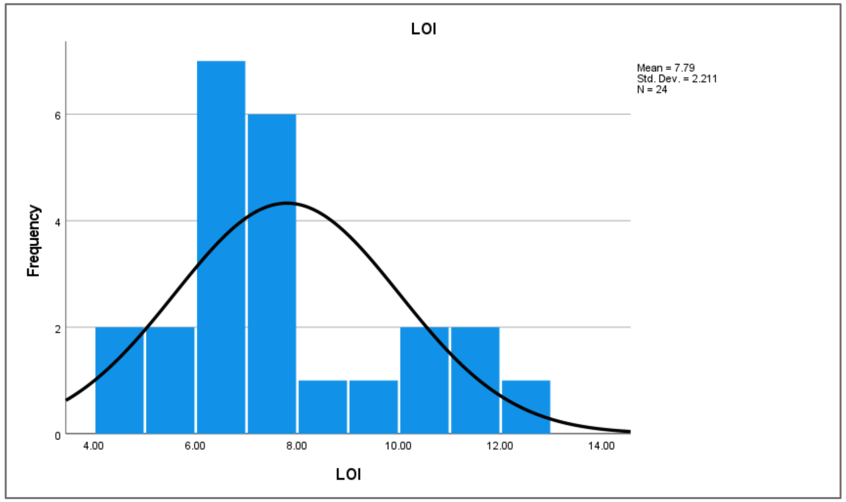
Statistics	Al	Ba	Ca	Cl	Cr	Fe	K	Mn	P	Rb	S	Si	Sr	Ti	V	Zn	Zr	Cu	Mg	Pb
Mean	6.6165	0.0724	0.9707	0.0463	0.0121	3.0566	1.7059	0.2731	0.6292	0.0085	0.0808	27.2621	0.0202	0.5094	0.0089	0.0131	0.0202	0.0039	0.6906	0.0024
Median	6.6704	0.0708	0.8083	0.0448	0.0120	3.0172	1.7069	0.2048	0.5508	0.0086	0.0749	27.3631	0.0194	0.5078	0.0089	0.0093	0.0202	0.0031	0.6570	0.0019
SE	0.1051	0.0025	0.0958	0.0039	0.0003	0.0793	0.0246	0.0537	0.0352	0.0001	0.0052	0.4164	0.0008	0.0049	0.0003	0.0021	0.0002	0.0005	0.0291	0.0004
SD	0.5151	0.0123	0.4692	0.0193	0.0012	0.3886	0.1206	0.2629	0.1726	0.0004	0.0255	2.0397	0.0041	0.0238	0.0016	0.0104	0.0012	0.0023	0.1426	0.0022
Max	7.5148	0.1002	2.3202	0.0984	0.0156	3.8802	1.9114	1.1096	1.1188	0.0092	0.1510	31.2102	0.0312	0.5518	0.0120	0.0486	0.0220	0.0098	1.0274	0.0112
Min	5.2768	0.0524	0.5994	0.0176	0.0106	2.4314	1.4520	0.0248	0.3978	0.0078	0.0414	22.8672	0.0152	0.4698	0.0068	0.0048	0.0168	0.0015	0.4934	0.0010

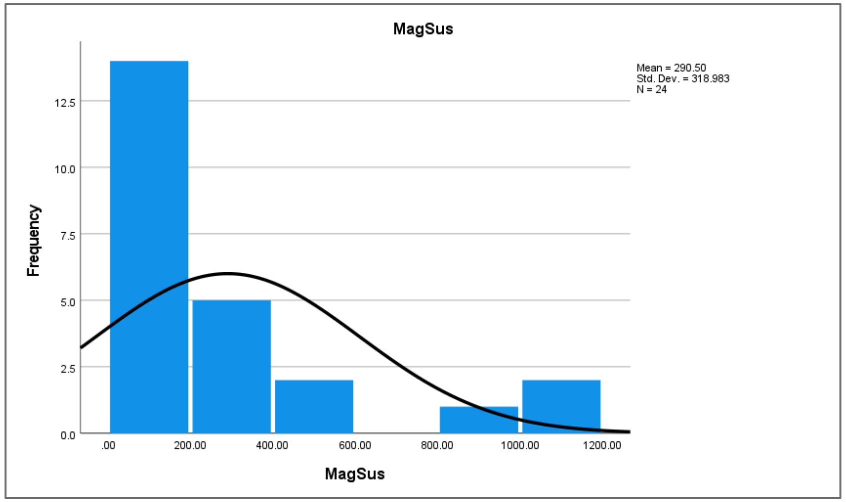
[1] Non-detect substituted with LOD/2 = 0.0040
[2] Non-detect substituted with LOD/2 = 0.0015
[3] Non-detect substituted with LOD/2 = 0.0430
[4] Non-detect substituted with LOD/2 = 0.0010
* Elements with number of non-detect values greater than 25%

Sheet 3: Normality of geochemical and magnetic variables

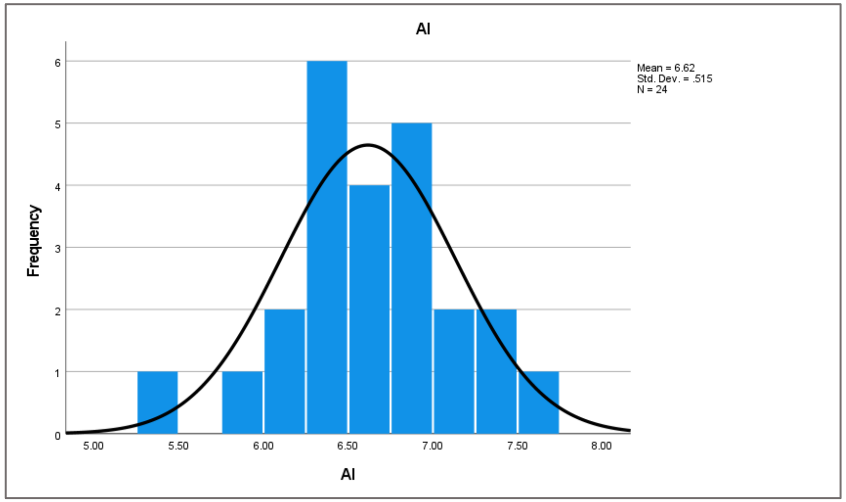


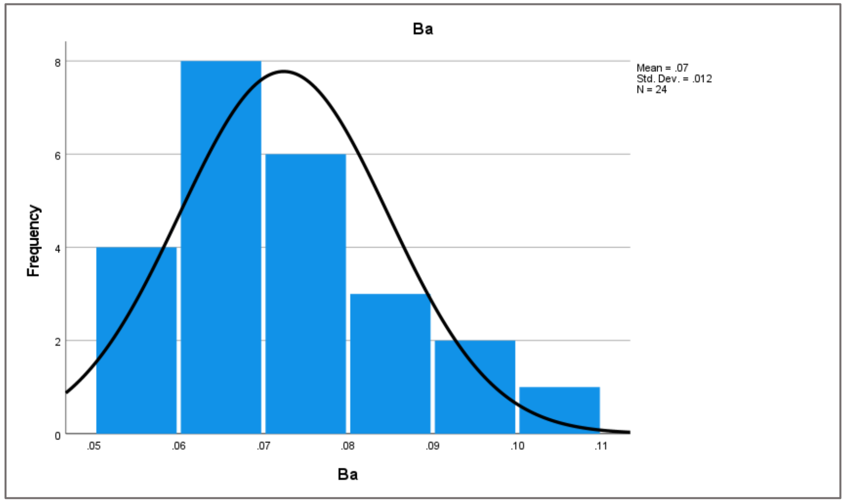


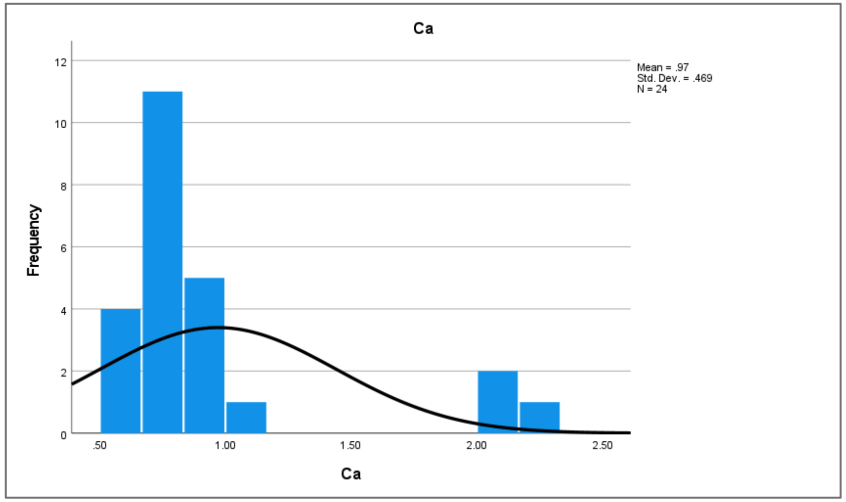


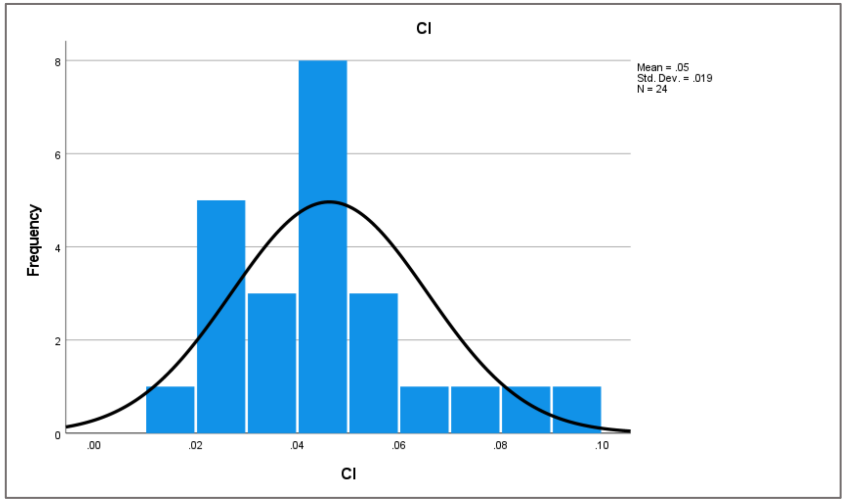


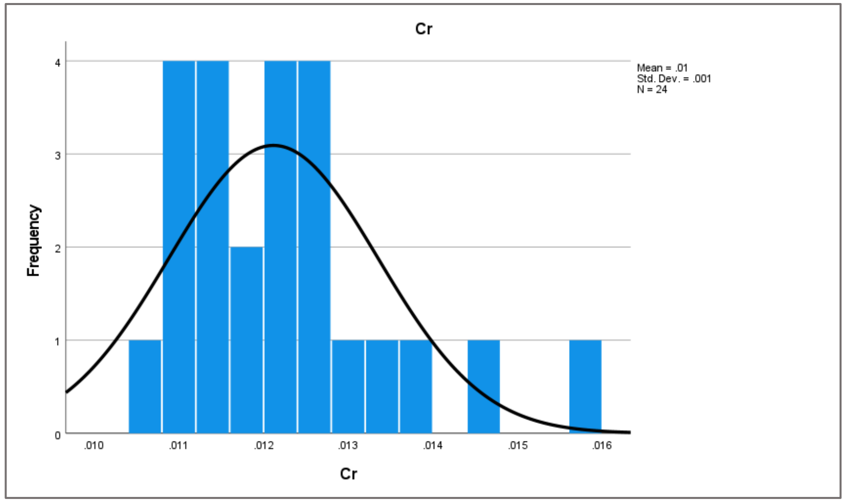
Sheet 4: Normality of multi-element variables

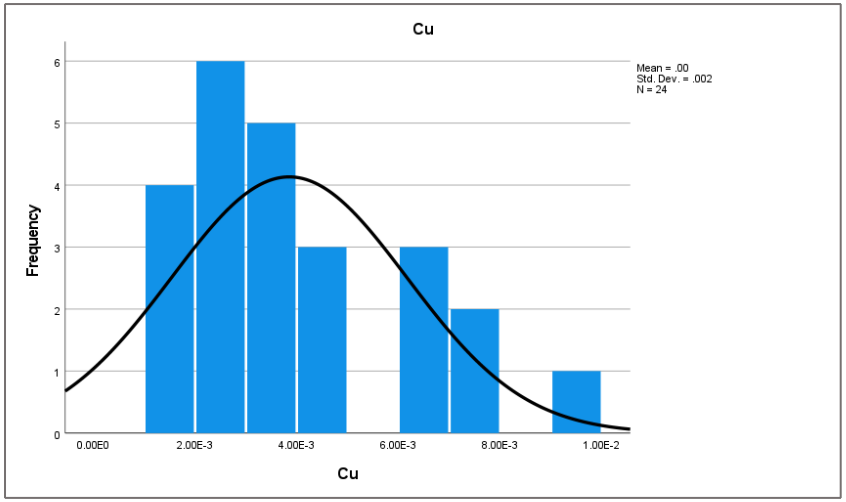


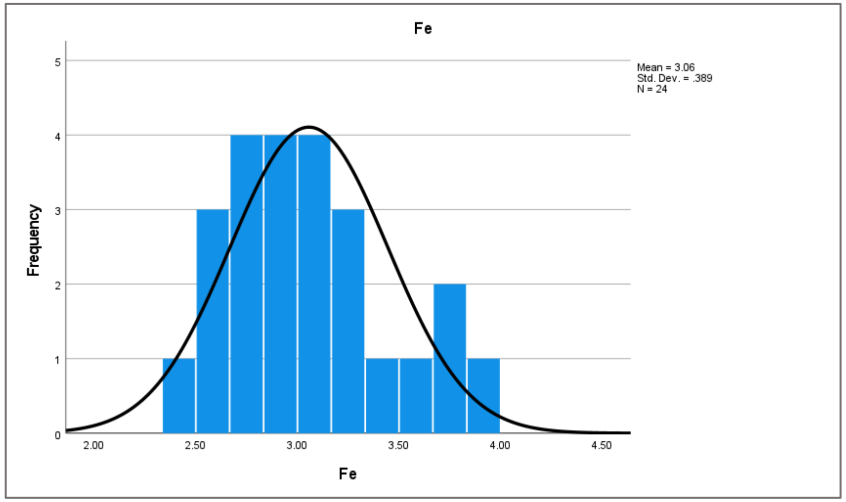


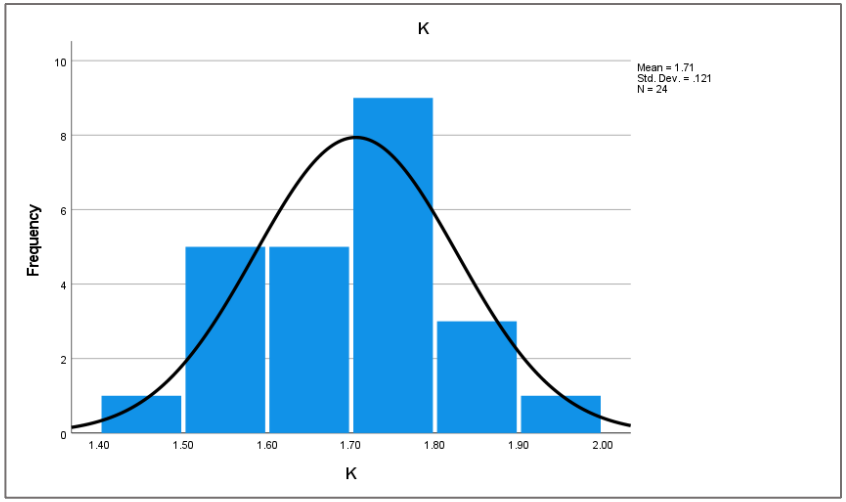


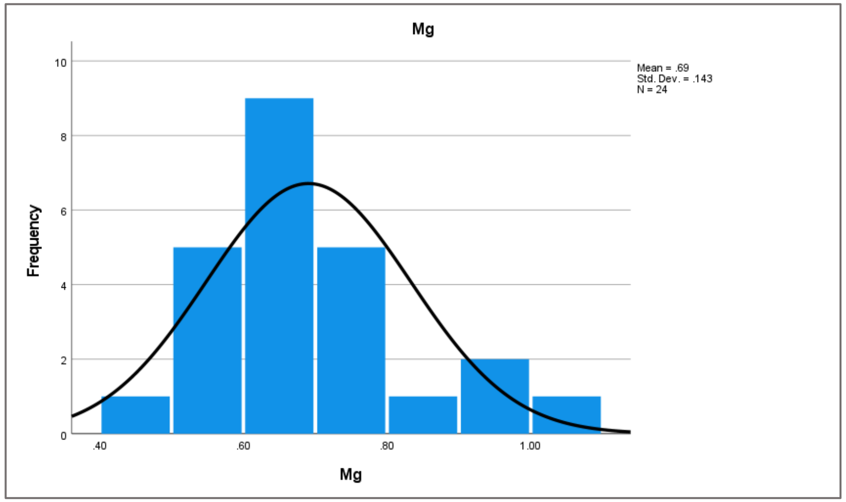


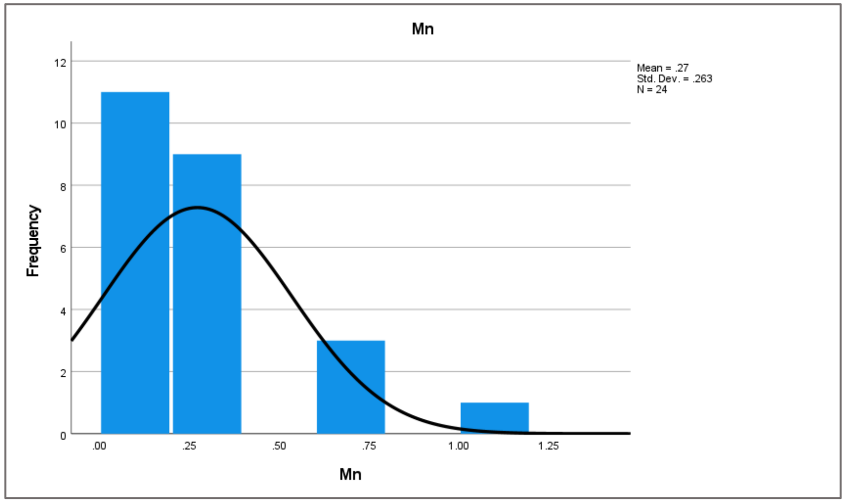

Cr
Mean = .01
Std. Dev. = .001
N = 24
Frequency
Cr

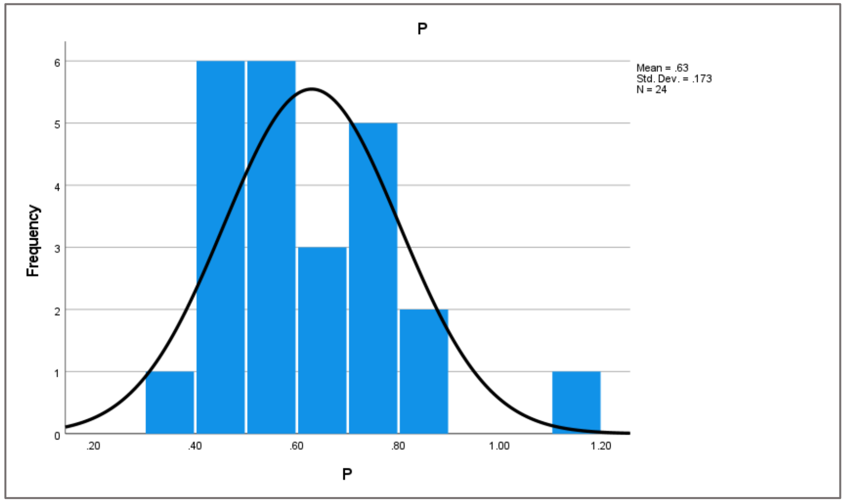

Cu
Mean = .00
Std. Dev. = .002
N = 24
Frequency
Cu

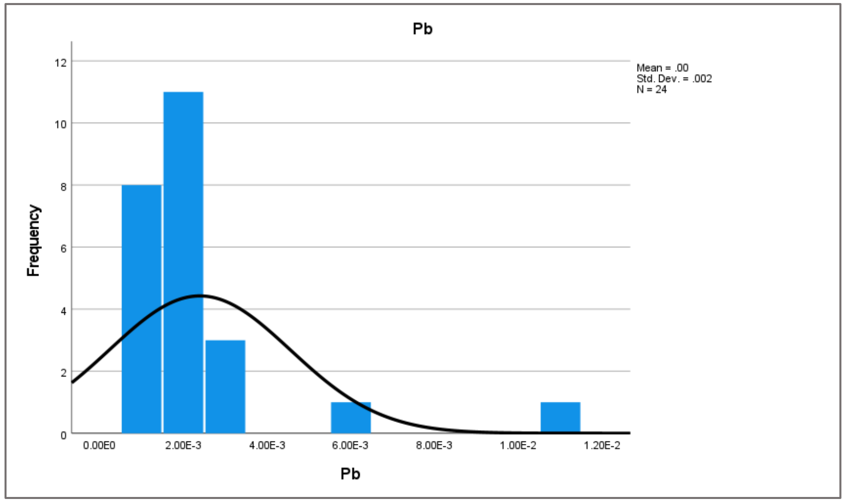

Fe
Mean = 3.06
Std. Dev. = .389
N = 24
Frequency
Fe

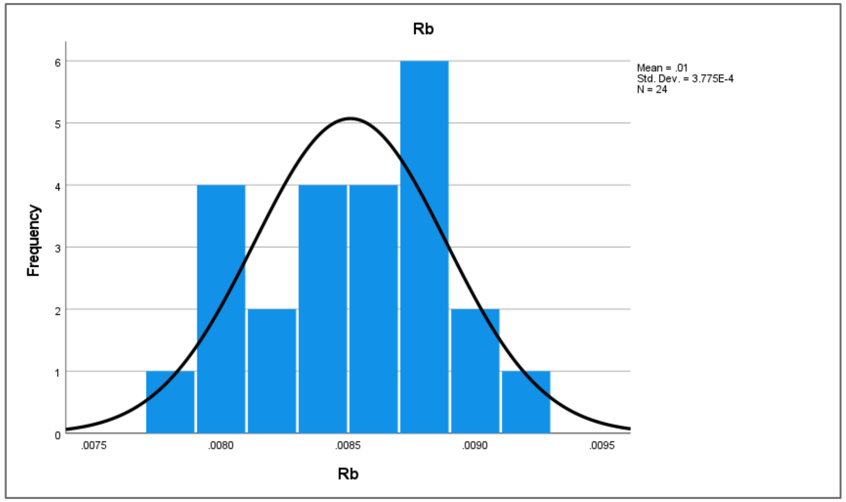

K
Mean = 1.71
Std. Dev. = .121
N = 24
Frequency
K

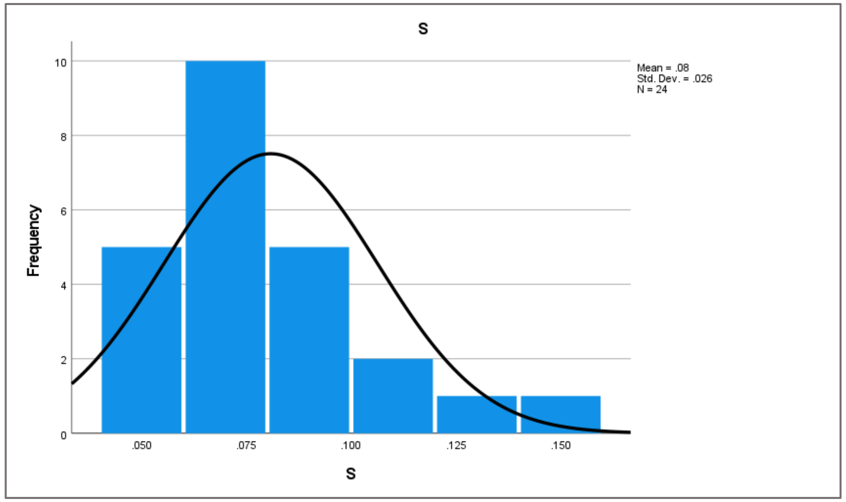

Mg
Mean = .69
Std. Dev. = .143
N = 24
Frequency
Mg

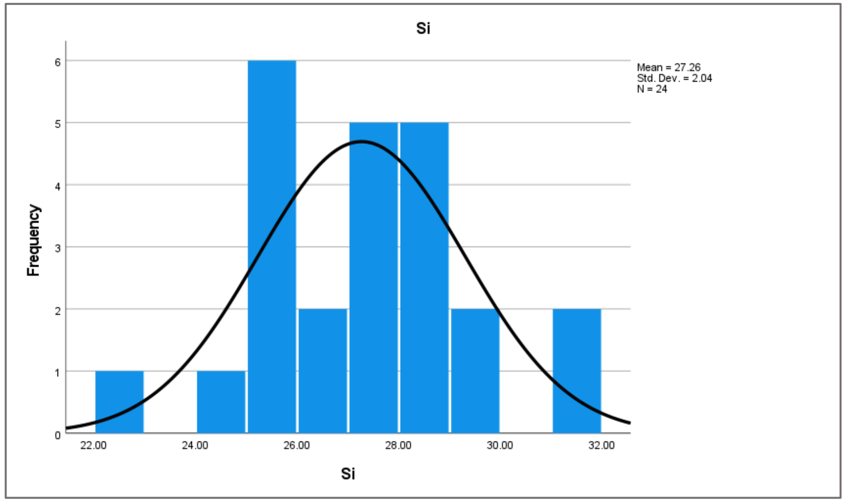

Mn
Mean = .27
Std. Dev. = .263
N = 24
Frequency
Mn

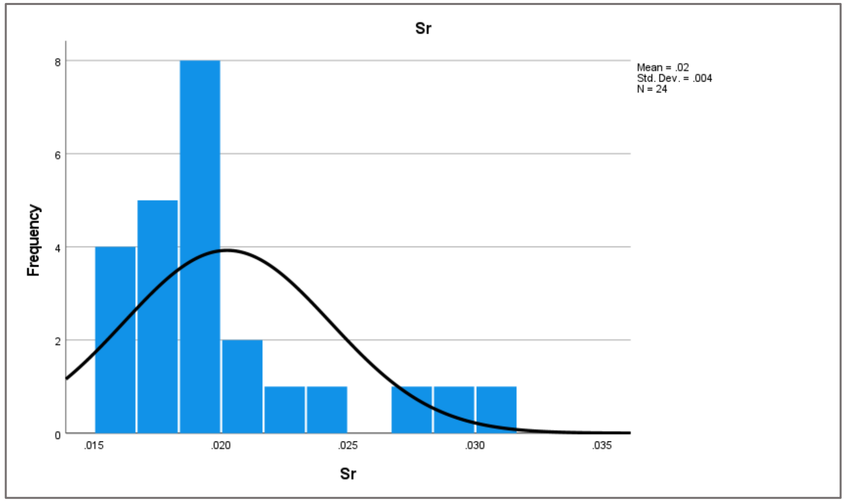

P
Mean = .63
Std. Dev. = .173
N = 24
Frequency
P

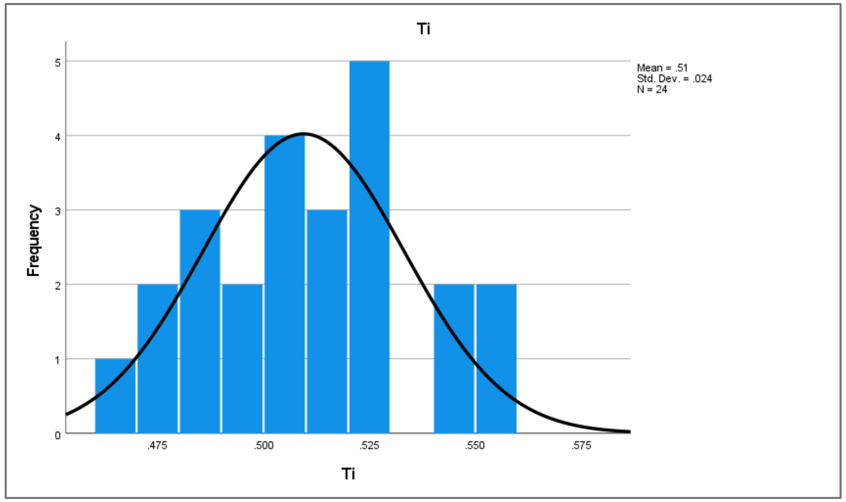

Pb
Mean = .00
Std. Dev. = .002
N = 24
Frequency
Pb

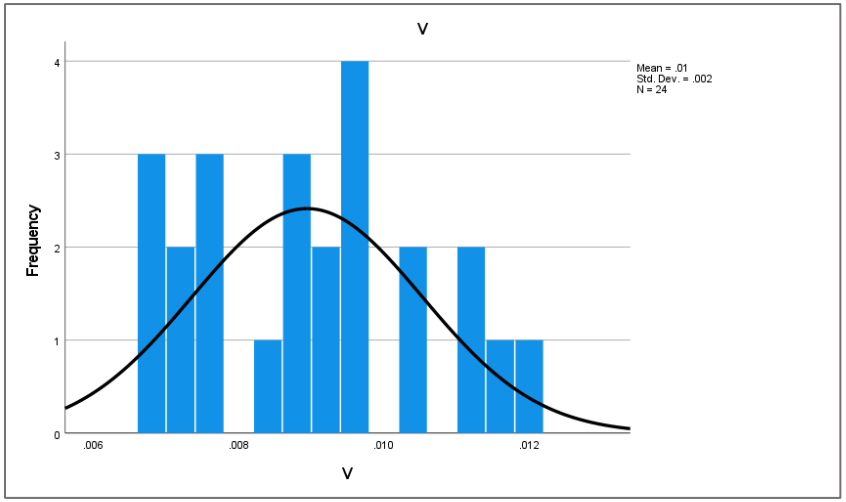

Rb
Mean = .01
Std. Dev. = 3.775E-4
N = 24
Frequency
Rb

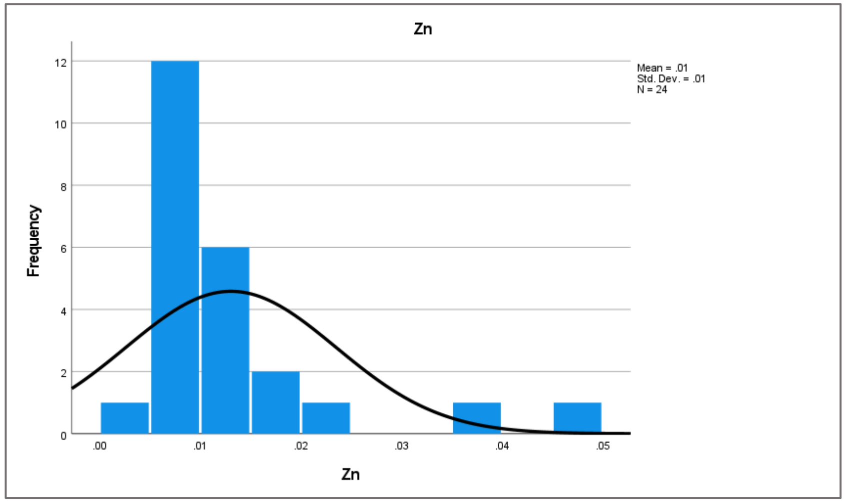

S
Mean = .08
Std. Dev. = .026
N = 24
Frequency
S

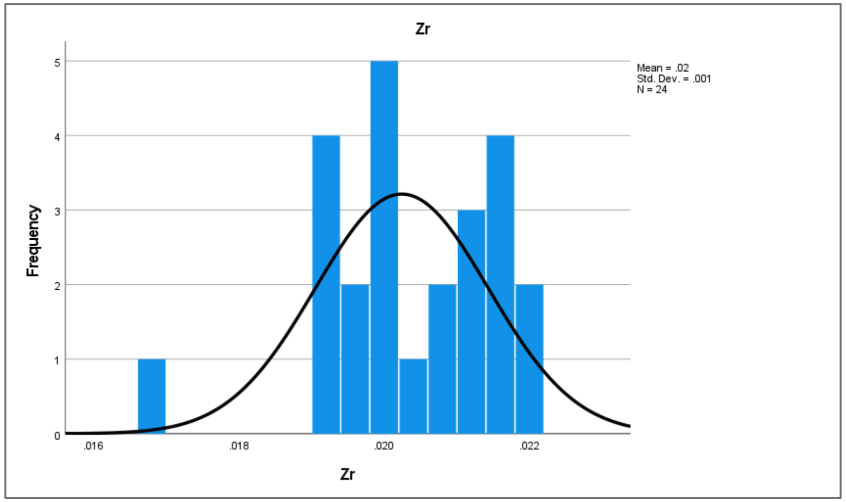

Si
Mean = 27.26
Std. Dev. = 2.04
N = 24
Frequency
Si


Sr
Mean = .02
Std. Dev. = .004
N = 24
Frequency
Sr

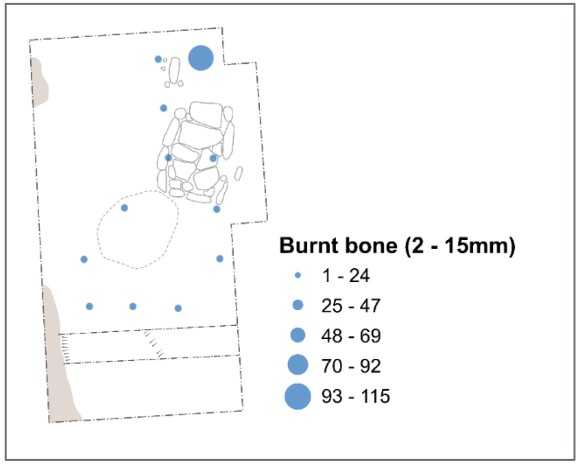

Ti
Mean = .51
Std. Dev. = .024
N = 24
Frequency
Ti

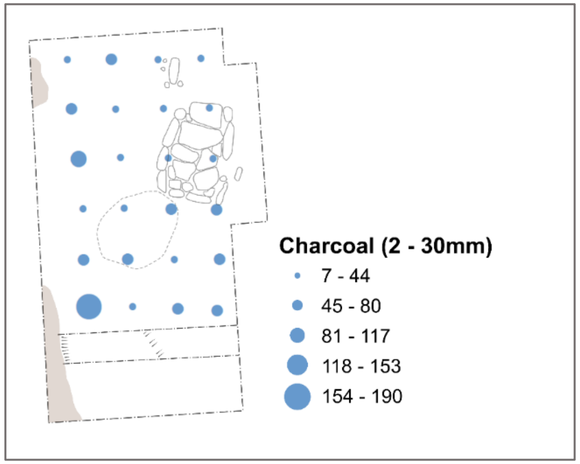

V
Mean = .01
Std. Dev. = .002
N = 24
Frequency
V

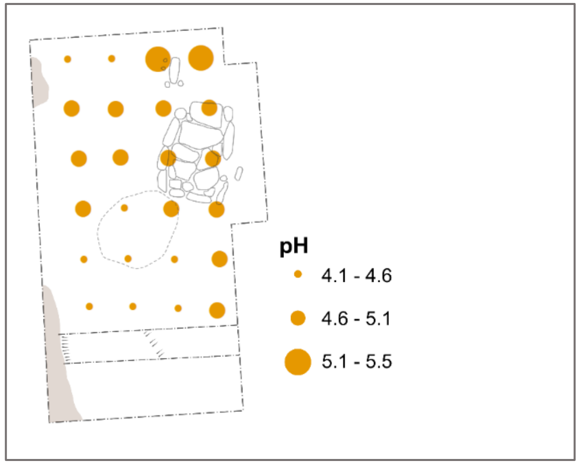

Zn
Mean = .01
Std. Dev. = .01
N = 24
Frequency
Zn

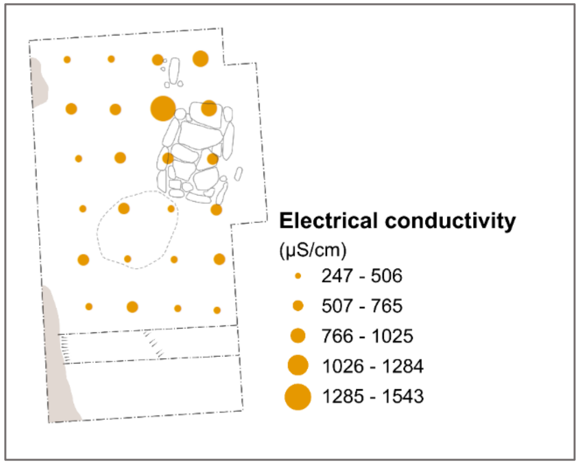

Zr
Mean = .02
Std. Dev. = .001
N = 24
Frequency
Zr

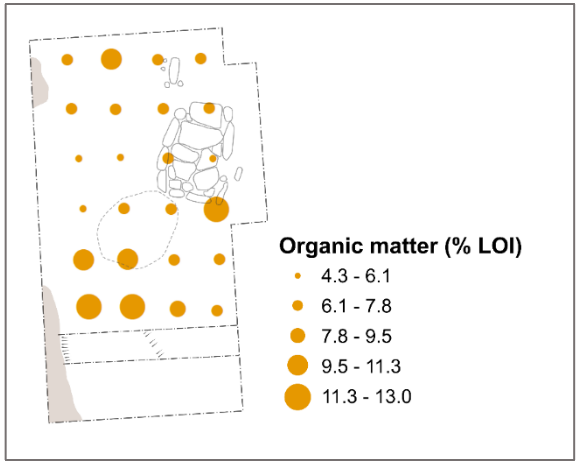
Sheet 5: Distribution of microrefuse, geochemical and magnetic variables

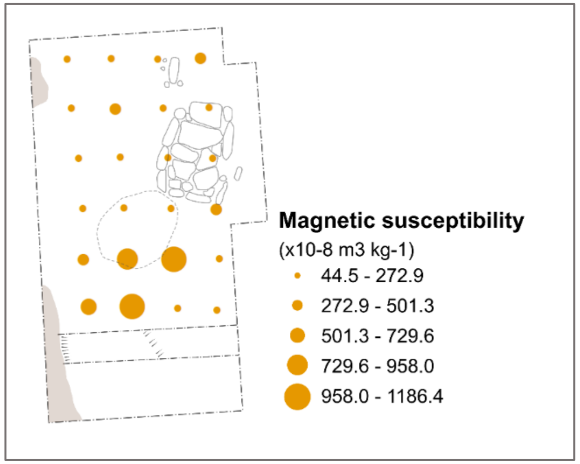




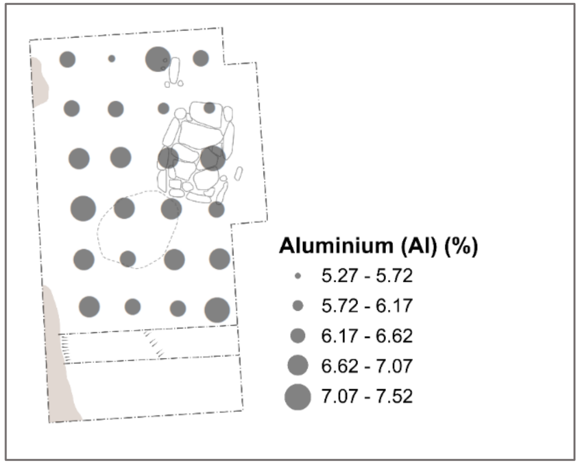


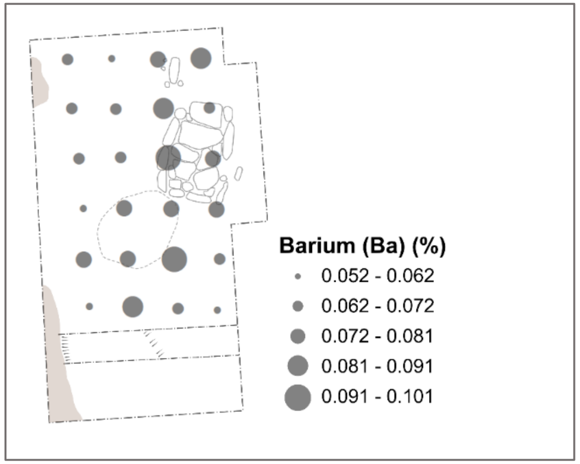


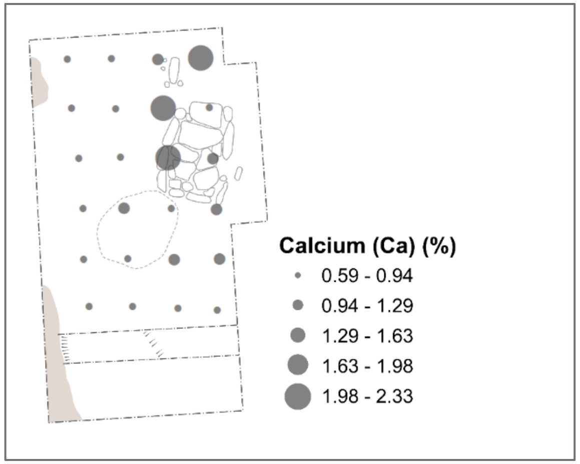


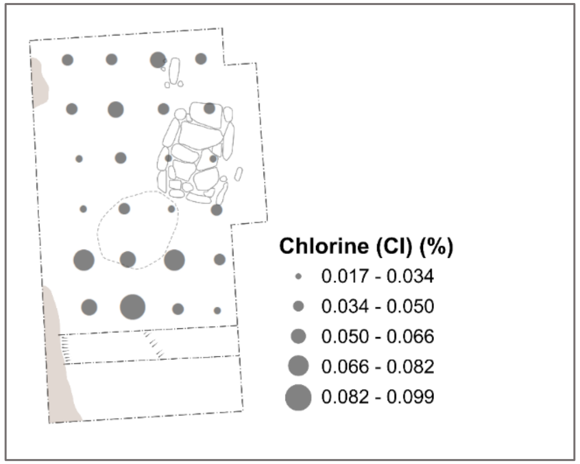


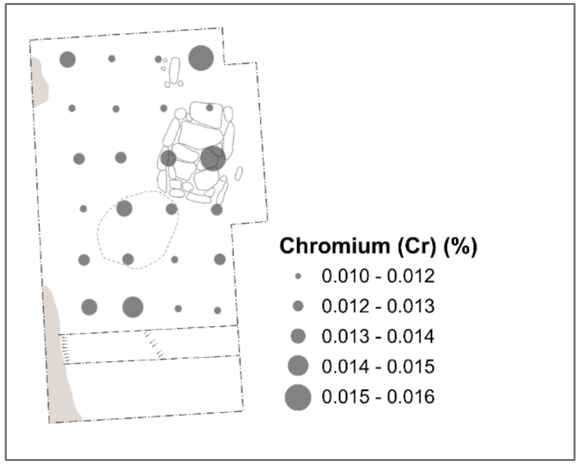
Sheet 6: Distribution of multi-element variables

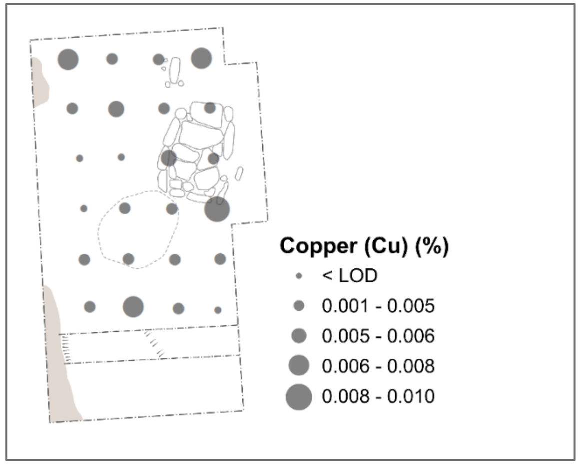


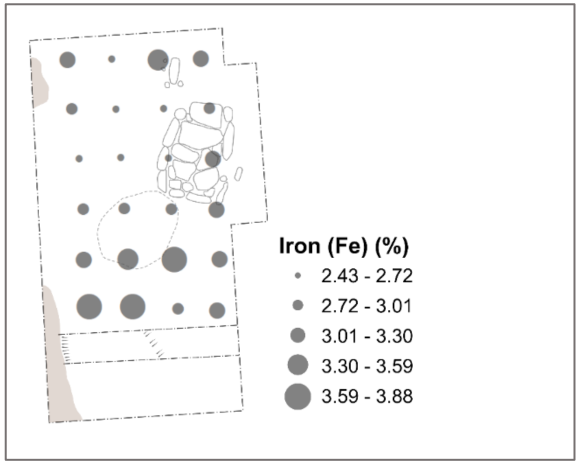


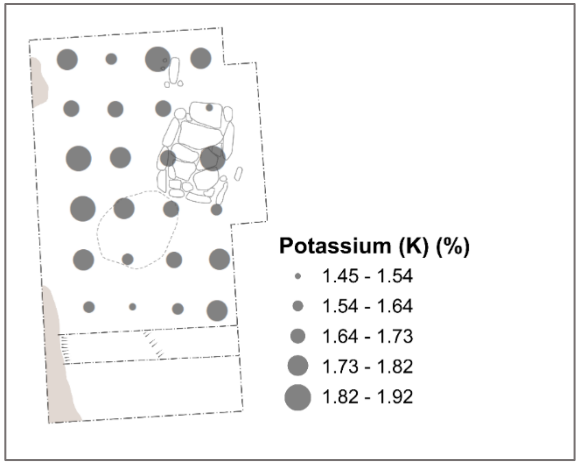


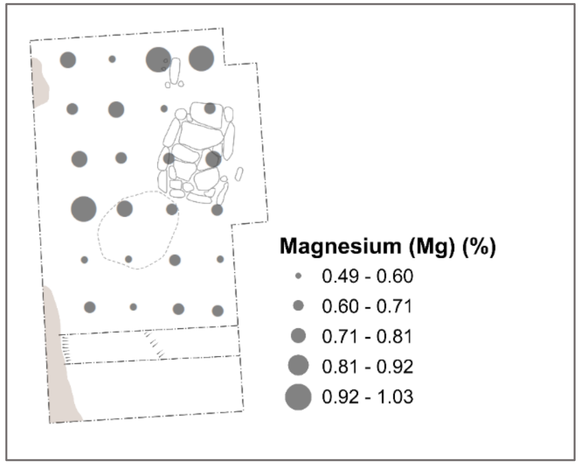


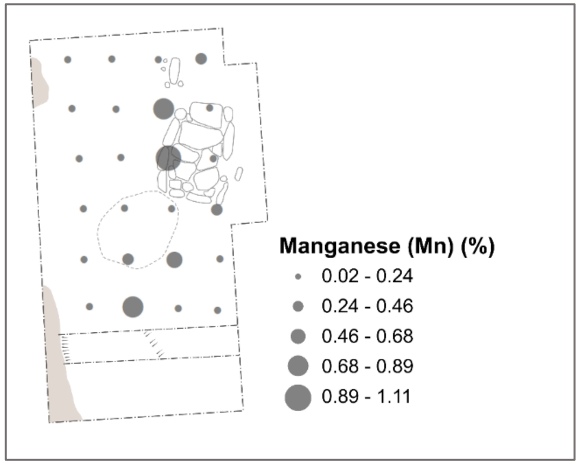


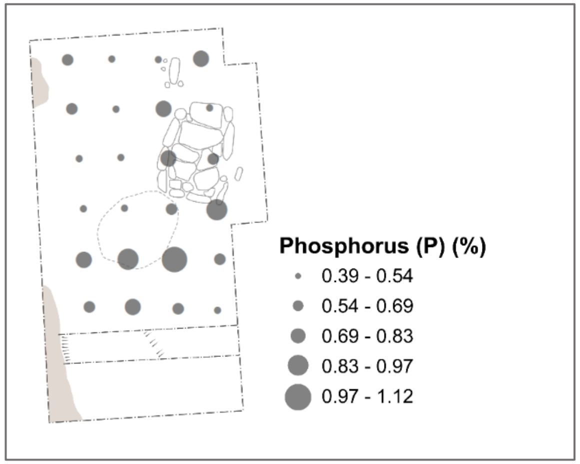


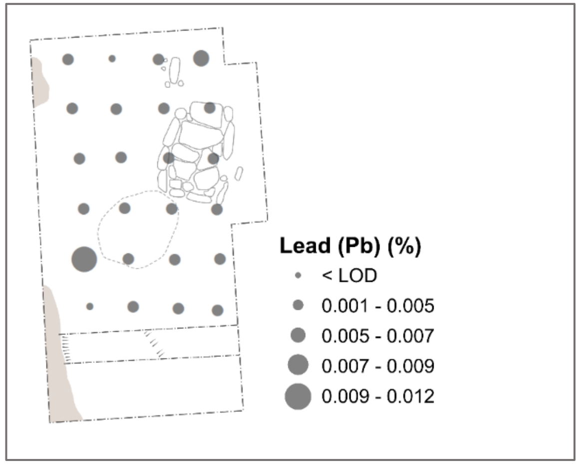

Iron (Fe) (%)
2.43 - 2.72
2.72 - 3.01
3.01 - 3.30
3.30 - 3.59
3.59 - 3.88

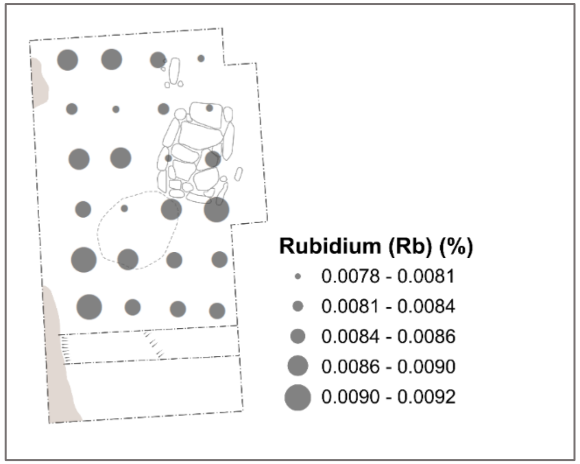

Potassium (K) (%)
1.45 - 1.54
1.54 - 1.64
1.64 - 1.73
1.73 - 1.82
1.82 - 1.92

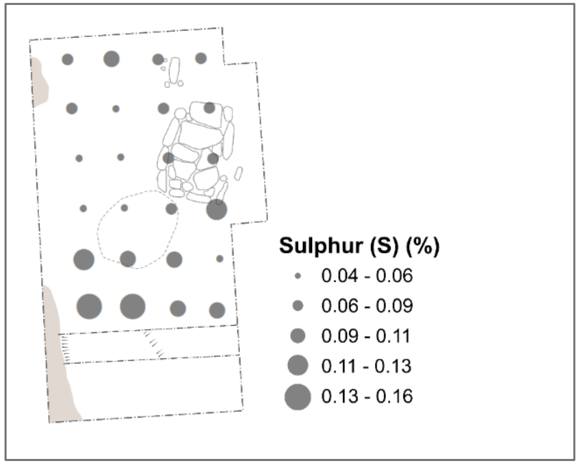

Magnesium (Mg) (%)
0.49 - 0.60
0.60 - 0.71
0.71 - 0.81
0.81 - 0.92
0.92 - 1.03

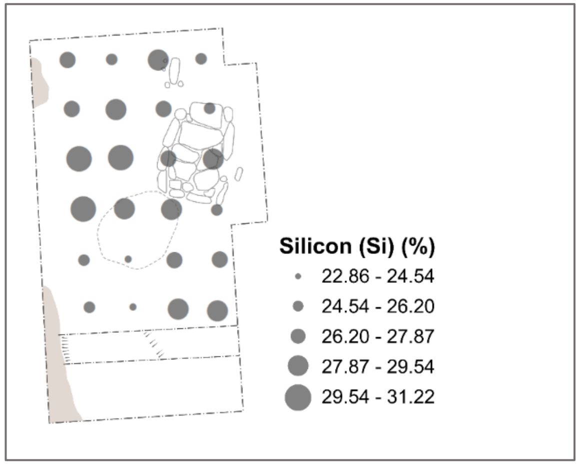

Manganese (Mn) (%)
0.02 - 0.24
0.24 - 0.46
0.46 - 0.68
0.68 - 0.89
0.89 - 1.11

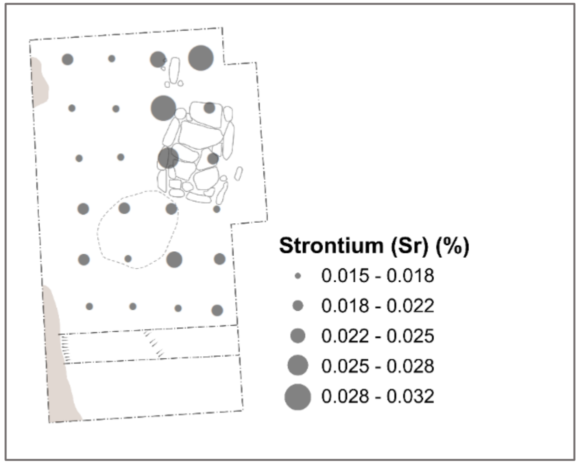

Phosphorus (P) (%)
0.39 - 0.54
0.54 - 0.69
0.69 - 0.83
0.83 - 0.97
0.97 - 1.12

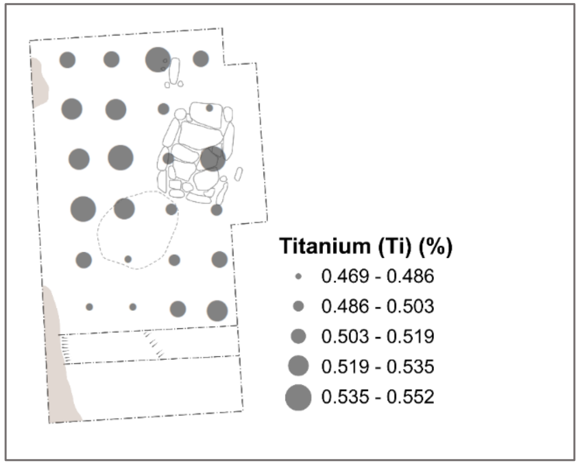

Lead (Pb) (%)
< LOD
0.001 - 0.005
0.005 - 0.007
0.007 - 0.009
0.009 - 0.012

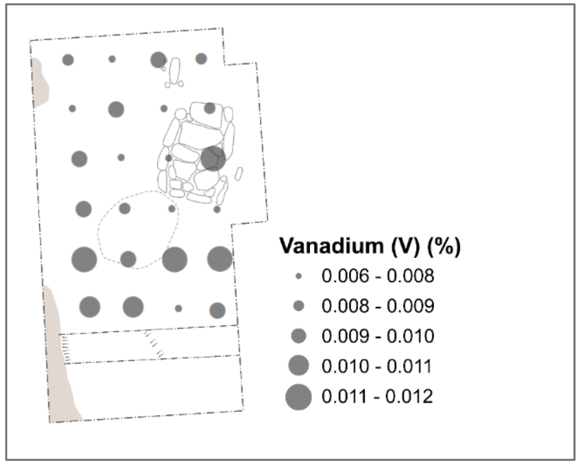

Rubidium (Rb) (%)
0.0078 - 0.0081
0.0081 - 0.0084
0.0084 - 0.0086
0.0086 - 0.0090
0.0090 - 0.0092

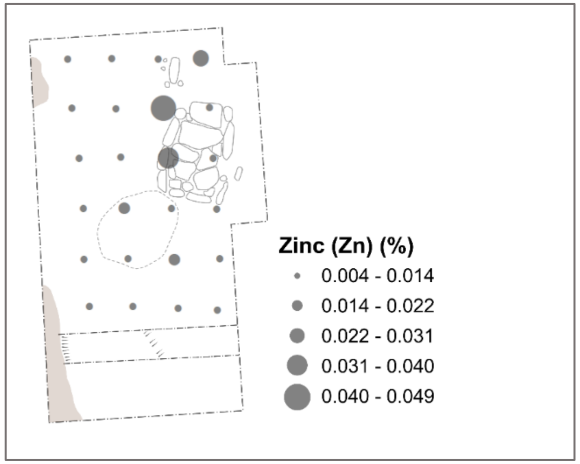

Sulphur (S) (%)
0.04 - 0.06
0.06 - 0.09
0.09 - 0.11
0.11 - 0.13
0.13 - 0.16

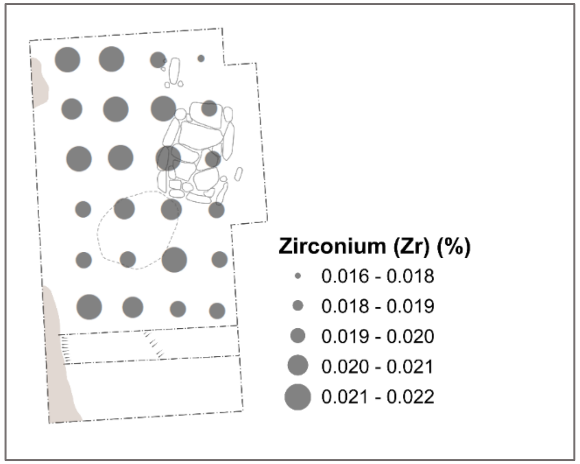

Silicon (Si) (%)
22.86 - 24.54
24.54 - 26.20
26.20 - 27.87
27.87 - 29.54
29.54 - 31.22


Strontium (Sr) (%)
0.015 - 0.018
0.018 - 0.022
0.022 - 0.025
0.025 - 0.028
0.028 - 0.032


Titanium (Ti) (%)
0.469 - 0.486
0.486 - 0.503
0.503 - 0.519
0.519 - 0.535
0.535 - 0.552


Vanadium (V) (%)
0.006 - 0.008
0.008 - 0.009
0.009 - 0.010
0.010 - 0.011
0.011 - 0.012


Zinc (Zn) (%)
0.004 - 0.014
0.014 - 0.022
0.022 - 0.031
0.031 - 0.040
0.040 - 0.049


Zirconium (Zr) (%)
0.016 - 0.018
0.018 - 0.019
0.019 - 0.020
0.020 - 0.021
0.021 - 0.022

Appendix 3

Statistical Readouts

The following appendix contains statistical readouts produced during analysis in SPSS and Origin Lab. It contains information regarding outliers (extreme values and box-and-whisker plots) and factor analysis (correlation matrices, KMO and Bartlett's tests, communalities, variance, scree plots and component matrices) for all sites. As the Lair dataset was also subjected to k-means clustering, additional readouts are provided for cluster analysis of the individual grid points and variables.

Each of the readouts have been grouped according to their sites and are presented in the order they appear in the main body of the thesis, namely:

- Lair
- Burghead (upper surface)
- Burghead (lower surface)
- Dunnicaer

Lair

Outliers

Factor Analysis

Hierarchical Analysis

Cluster Analysis

Outliers

Notes

Output Created		06-NOV-2022 15:02:27
Comments		
Input	Data	C: \Users\vanes\Documents\PhD\Analysis\SPSS\Combined (Geochemical and Elements)\Combined (Geochemical and Elements).sav
	Active Dataset	DataSet6
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	180
Missing Value Handling	Definition of Missing	User-defined missing values for dependent variables are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any dependent variable or factor used.
Syntax		EXAMINE VARIABLES=pH EC LOI MagSus Al Ba Ca Cr Fe K Mn P Rb S Si Sr Ti V Zn Zr /PLOT BOXPLOT /COMPARE GROUPS /STATISTICS DESCRIPTIVES EXTREME /CINTERVAL 95 /MISSING LISTWISE...
Resources	Processor Time	00:00:05.24
	Elapsed Time	00:00:06.15

Extreme Values

			Case Number	Value
pH	Highest	1	13	4.7
		2	15	4.5
		3	26	4.3
		4	45	4.3
		5	61	4.3[a]
	Lowest	1	144	3.2
		2	135	3.2
		3	175	3.3
		4	167	3.3
		5	154	3.3[b]
EC	Highest	1	160	1069
		2	133	994
		3	136	988
		4	66	900
		5	59	879
	Lowest	1	13	99
		2	116	134
		3	163	145
		4	25	154
		5	162	161[c]
LOI	Highest	1	160	27.4
		2	114	22.9
		3	137	22.7
		4	113	21.6
		5	10	21.0
	Lowest	1	60	4.7
		2	49	5.8
		3	82	5.9
		4	61	6.0
		5	38	6.0
MagSus	Highest	1	151	853.5
		2	168	667.8
		3	127	666.6
		4	126	609.6
		5	152	609.2
	Lowest	1	26	26.8
		2	160	28.3
		3	14	30.1

Extreme Values

			Case Number	Value
		4	1	37.9
		5	136	39.2[d]
Al	Highest	1	60	10.36
		2	49	10.26
		3	61	9.88
		4	50	9.75
		5	82	9.59
	Lowest	1	160	5.10
		2	137	5.78
		3	114	5.94
		4	113	5.97
		5	68	6.04
Ba	Highest	1	38	.074
		2	60	.073
		3	61	.069
		4	23	.069
		5	49	.069
	Lowest	1	160	.031
		2	136	.035
		3	134	.036
		4	66	.039
		5	137	.039[e]
Ca	Highest	1	125	.99
		2	95	.84
		3	60	.72
		4	124	.72
		5	160	.69
	Lowest	1	137	.45
		2	10	.46
		3	114	.46
		4	11	.48
		5	116	.48
Cr	Highest	1	40	.0182
		2	152	.0174
		3	4	.0172
		4	23	.0170
		5	139	.0170

Extreme Values

			Case Number	Value
	Lowest	1	160	.0096
		2	134	.0098
		3	128	.0106
		4	158	.0108
		5	132	.0112[f]
Fe	Highest	1	23	5.94
		2	139	5.69
		3	27	5.53
		4	116	5.45
		5	51	5.45
	Lowest	1	160	2.38
		2	134	3.54
		3	166	3.69
		4	165	3.75
		5	43	3.82
K	Highest	1	49	2.49
		2	50	2.44
		3	60	2.42
		4	38	2.35
		5	61	2.28
	Lowest	1	160	1.56
		2	68	1.65
		3	114	1.68
		4	69	1.69
		5	137	1.70
Mn	Highest	1	151	.41
		2	126	.33
		3	123	.33
		4	103	.32
		5	127	.31
	Lowest	1	137	.01
		2	157	.02
		3	43	.02
		4	114	.02
		5	163	.02
P	Highest	1	125	.54
		2	23	.50
		3	61	.49

Extreme Values

			Case Number	Value
		4	10	.46
		5	40	.44
	Lowest	1	34	.18
		2	26	.18
		3	83	.20
		4	2	.21
		5	35	.21
Rb	Highest	1	8	.0124
		2	7	.0118
		3	19	.0118
		4	20	.0116
		5	29	.0116
	Lowest	1	160	.0066
		2	69	.0070
		3	68	.0072
		4	70	.0074
		5	141	.0076[g]
S	Highest	1	160	.196
		2	10	.155
		3	113	.151
		4	108	.146
		5	136	.141
	Lowest	1	60	.043
		2	38	.048
		3	61	.048
		4	82	.050
		5	49	.053
Si	Highest	1	178	25.95
		2	82	25.75
		3	176	25.63
		4	60	25.59
		5	174	25.50
	Lowest	1	10	17.52
		2	113	18.20
		3	114	18.44
		4	137	18.50
		5	116	18.86

Extreme Values

			Case Number	Value
Sr	Highest	1	174	.0160
		2	23	.0154
		3	91	.0152
		4	49	.0150
		5	60	.0150
	Lowest	1	137	.0104
		2	114	.0104
		3	68	.0110
		4	11	.0110
		5	134	.0112[f]
Ti	Highest	1	8	.75
		2	49	.75
		3	53	.75
		4	23	.75
		5	179	.74
	Lowest	1	160	.50
		2	113	.59
		3	68	.59
		4	124	.60
		5	26	.60
V	Highest	1	56	.0160
		2	23	.0158
		3	88	.0158
		4	24	.0156
		5	123	.0156
	Lowest	1	160	.0082
		2	65	.0106
		3	48	.0106
		4	153	.0110
		5	180	.0112[f]
Zn	Highest	1	123	.022
		2	124	.018
		3	125	.018
		4	38	.018
		5	126	.017
	Lowest	1	134	.003
		2	26	.004
		3	163	.004

Extreme Values

			Case Number	Value
		4	112	.004
		5	70	.004[h]
Zr	Highest	1	127	.032
		2	50	.030
		3	103	.029
		4	18	.029
		5	29	.029[i]
	Lowest	1	26	.021
		2	160	.021
		3	68	.021
		4	10	.022
		5	45	.022

a. Only a partial list of cases with the value 4.3 are shown in the table of upper extremes.

b. Only a partial list of cases with the value 3.3 are shown in the table of lower extremes.

c. Only a partial list of cases with the value 161 are shown in the table of lower extremes.

d. Only a partial list of cases with the value 39.2 are shown in the table of lower extremes.

e. Only a partial list of cases with the value .039 are shown in the table of lower extremes.

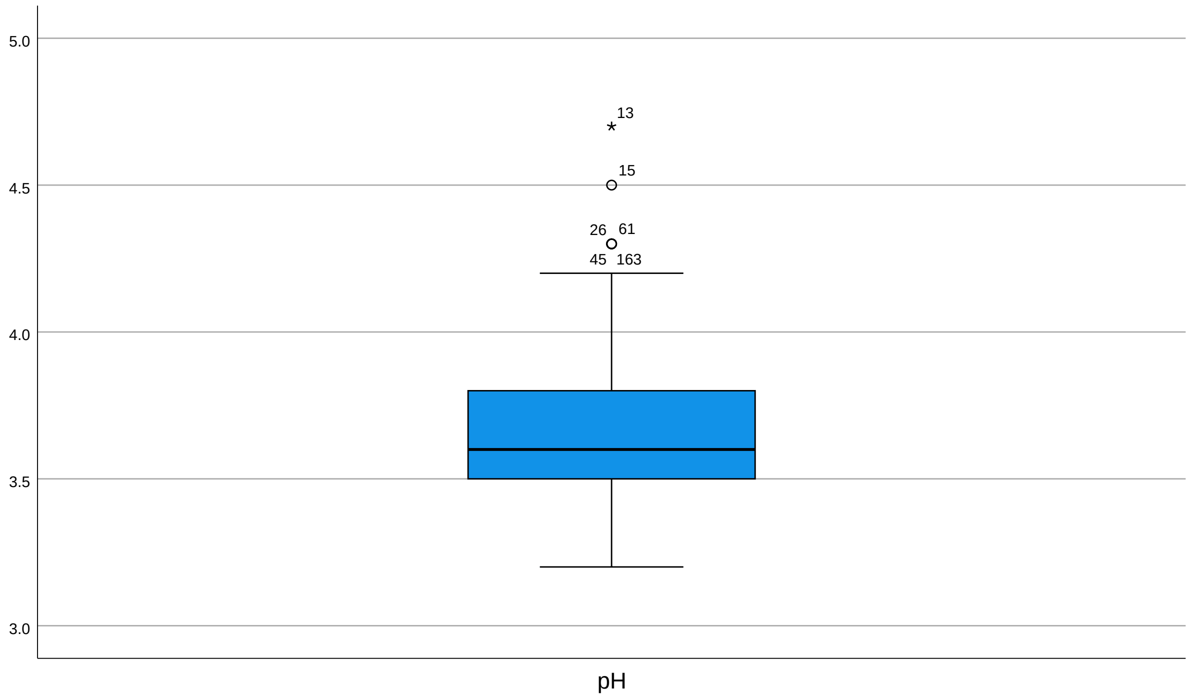
f. Only a partial list of cases with the value .0112 are shown in the table of lower extremes.

g. Only a partial list of cases with the value .0076 are shown in the table of lower extremes.

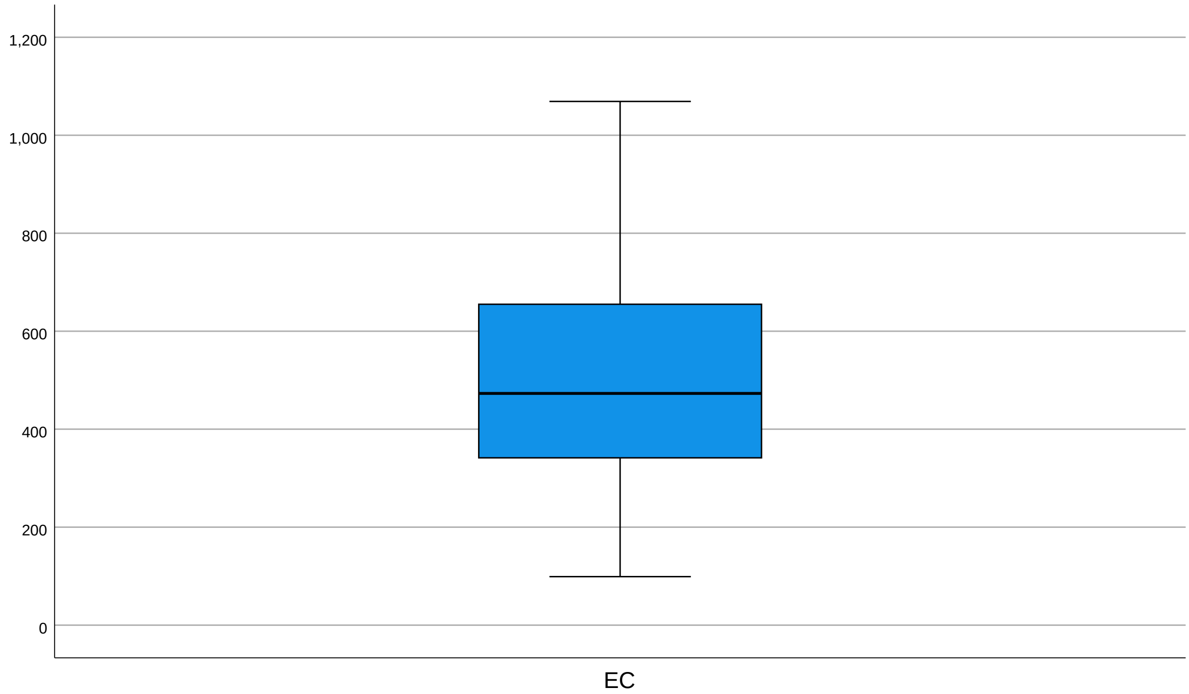
h. Only a partial list of cases with the value .004 are shown in the table of lower extremes.

i. Only a partial list of cases with the value .029 are shown in the table of upper extremes.

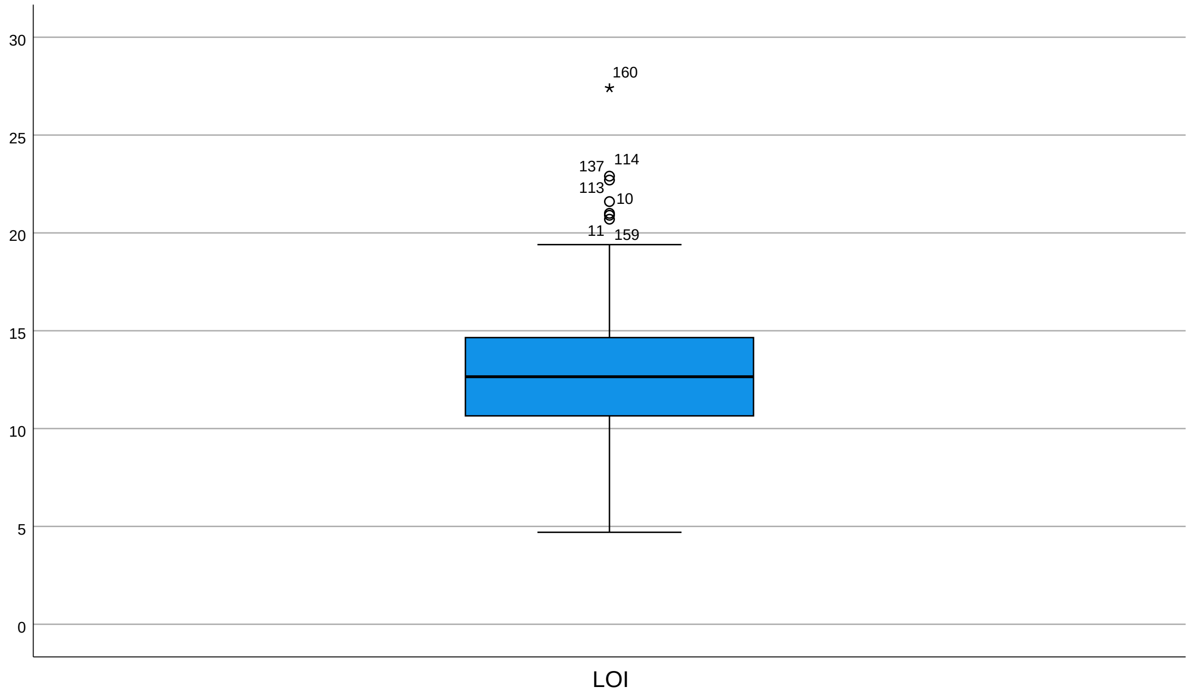
pH



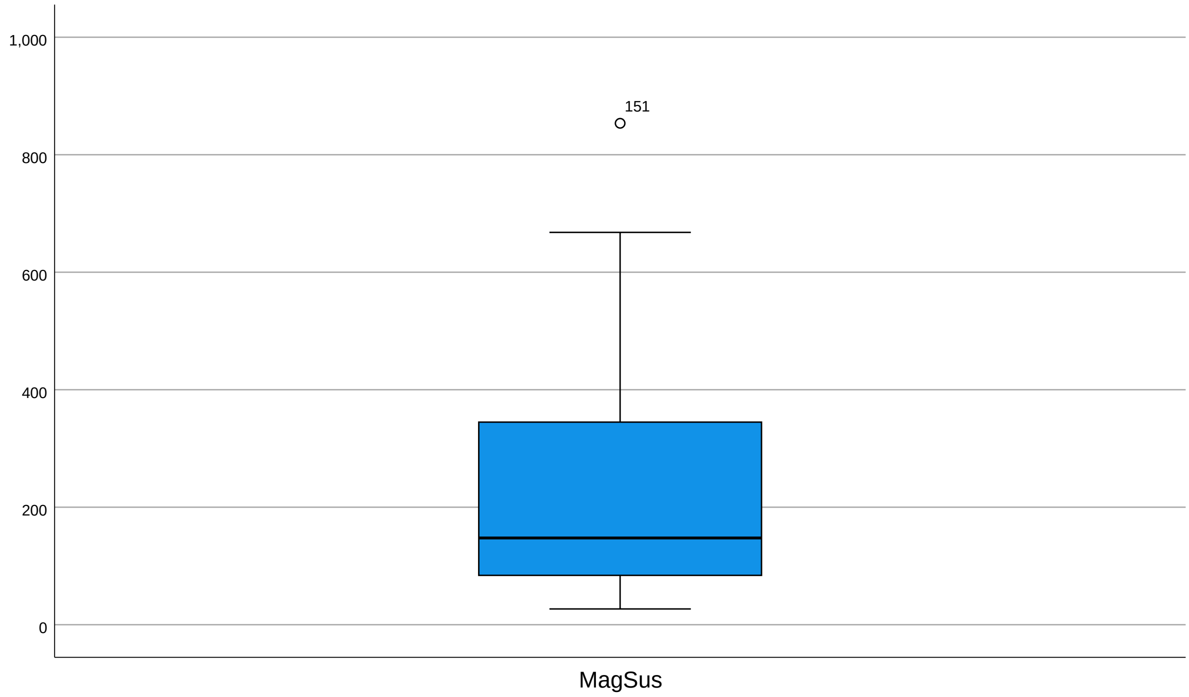
EC



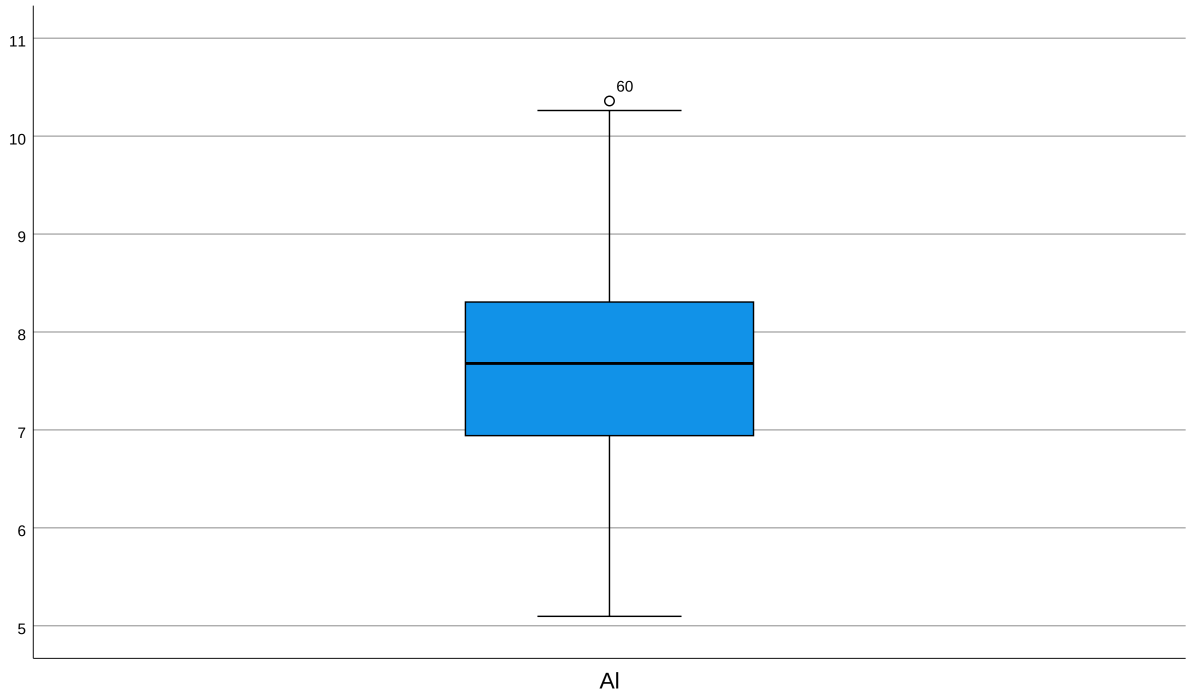
LOI


30
25
20
15
10
5
0
160
137
114
113
10
11
159
LOI

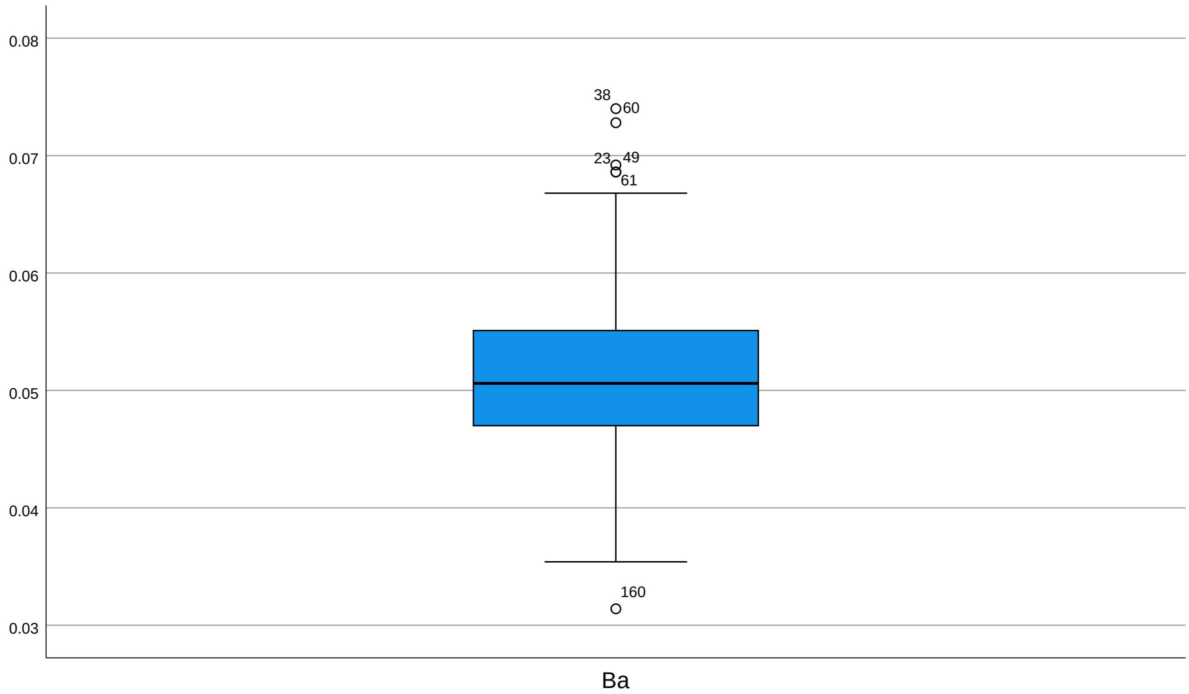
MagSus


1,000
800
600
400
200
0
151
MagSus

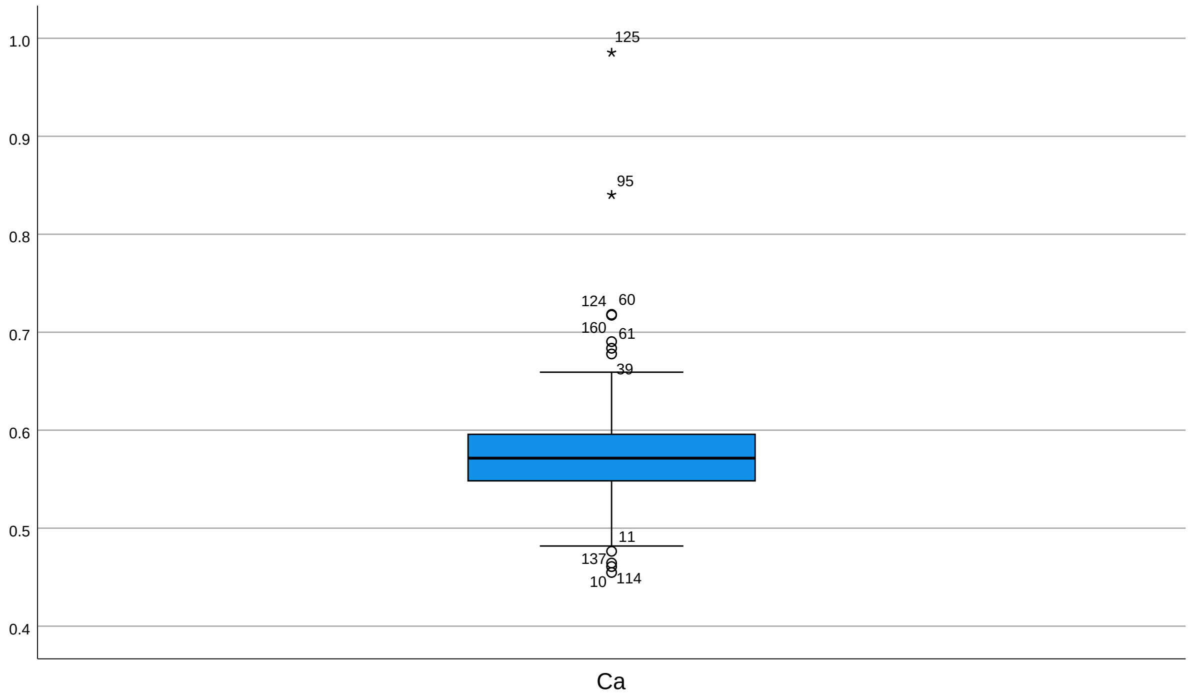
Al



Ba

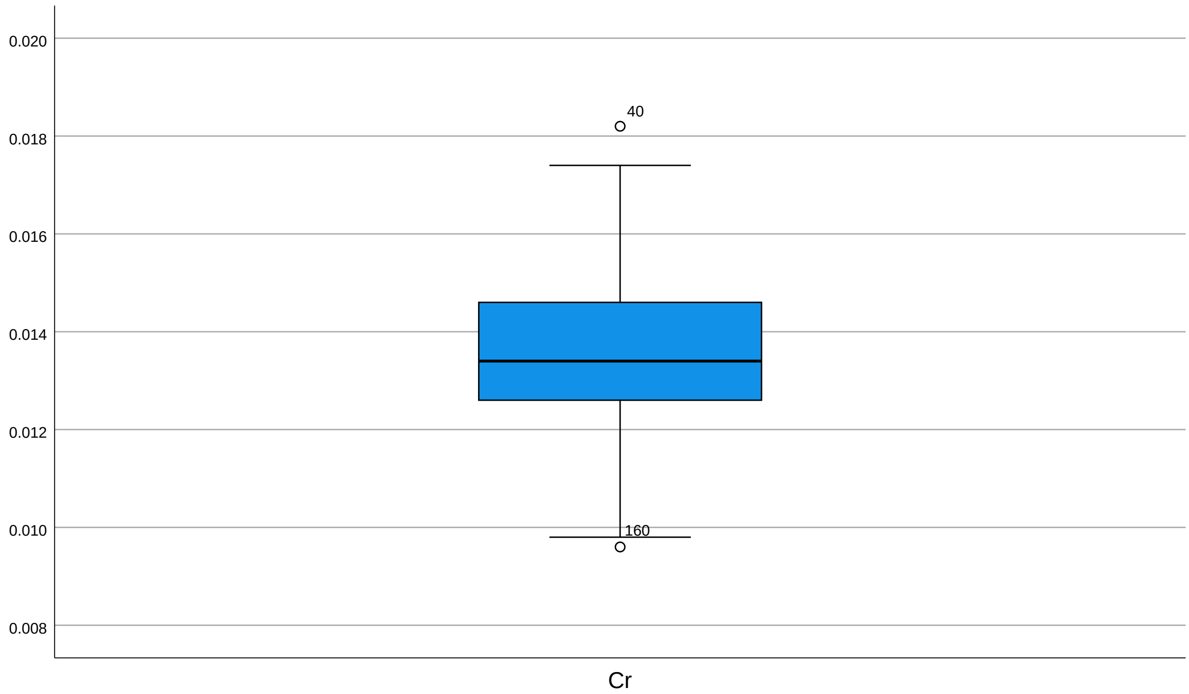


Ca



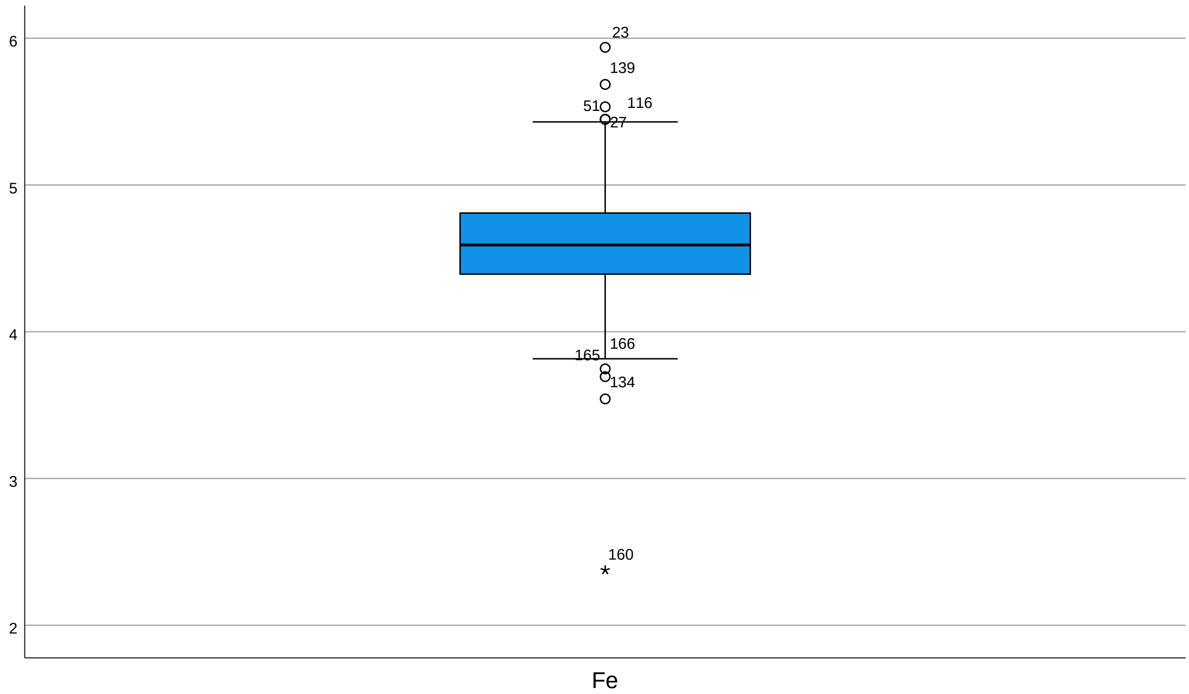
1.0
0.9
0.8
0.7
0.6
0.5
0.4
125
95
124
60
160
61
39
11
137
10
114
Ca

Cr

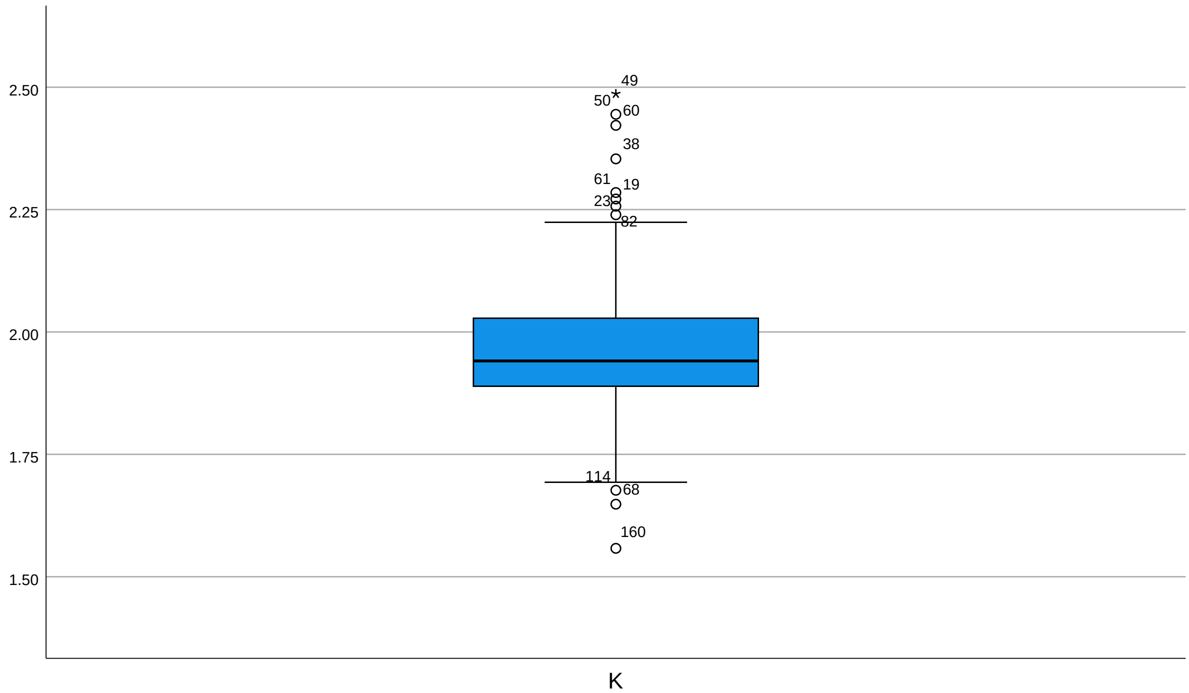


0.020
0.018
0.016
0.014
0.012
0.010
0.008
40
160
Cr

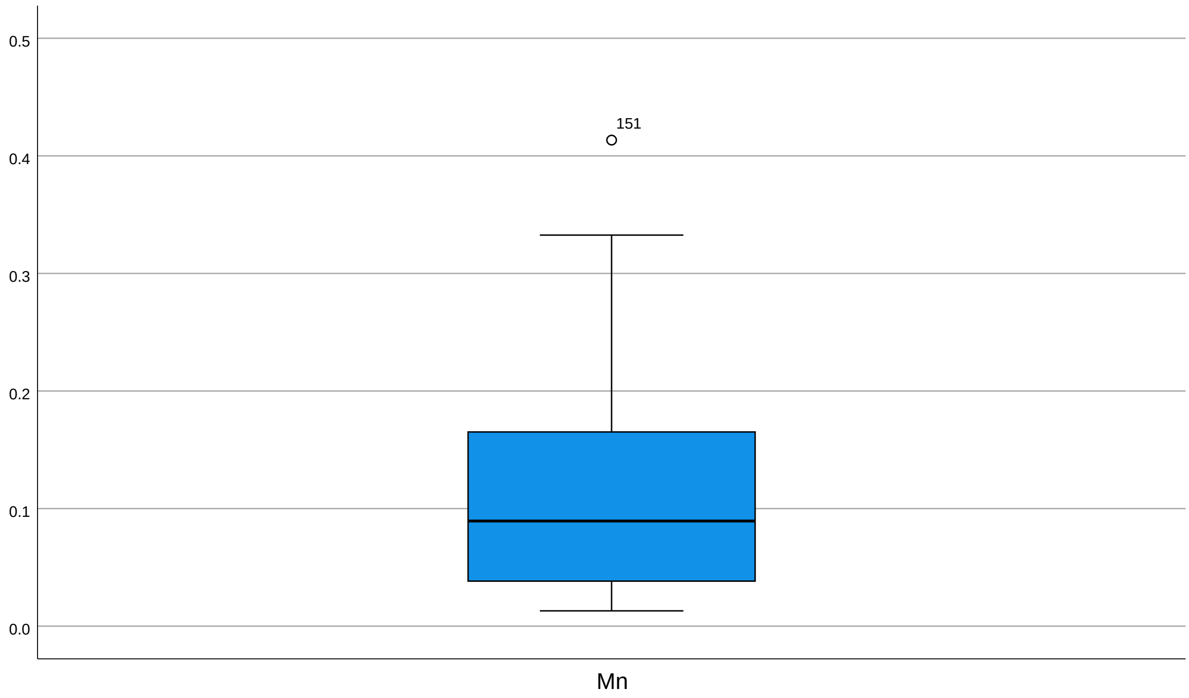
Fe


6
5
4
3
2
23
139
51
116
27
166
165
134
160
Fe

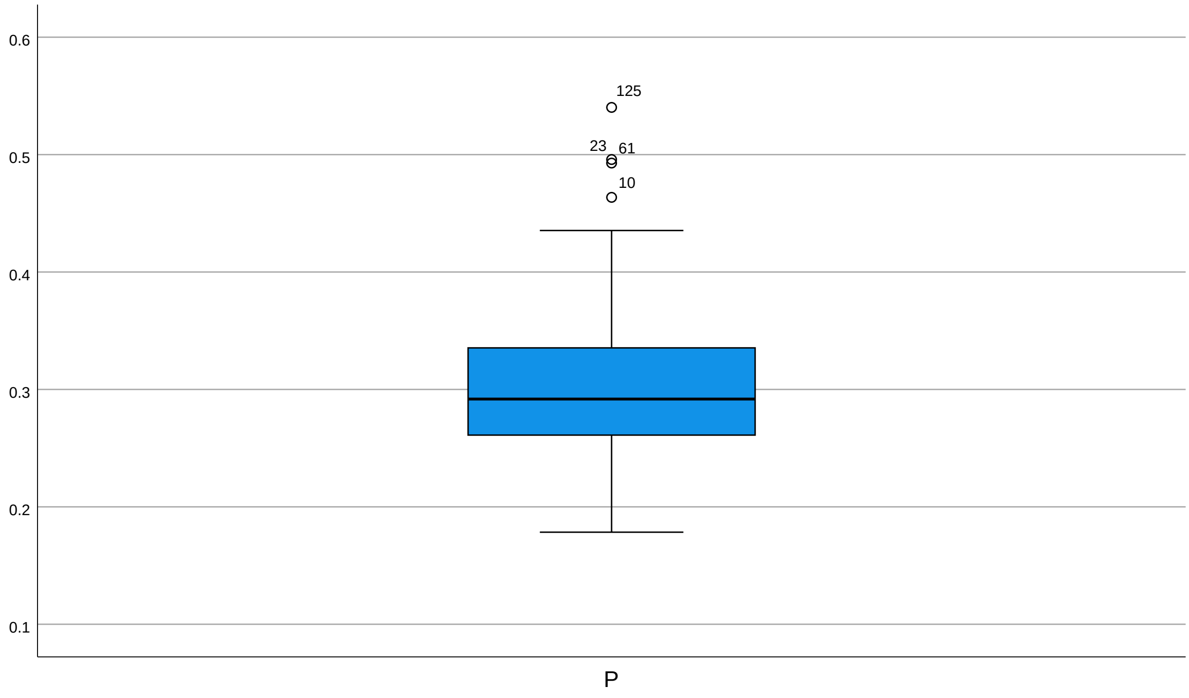
K


2.50
2.25
2.00
1.75
1.50
49
50
60
38
61
19
23
82
114
68
160
K

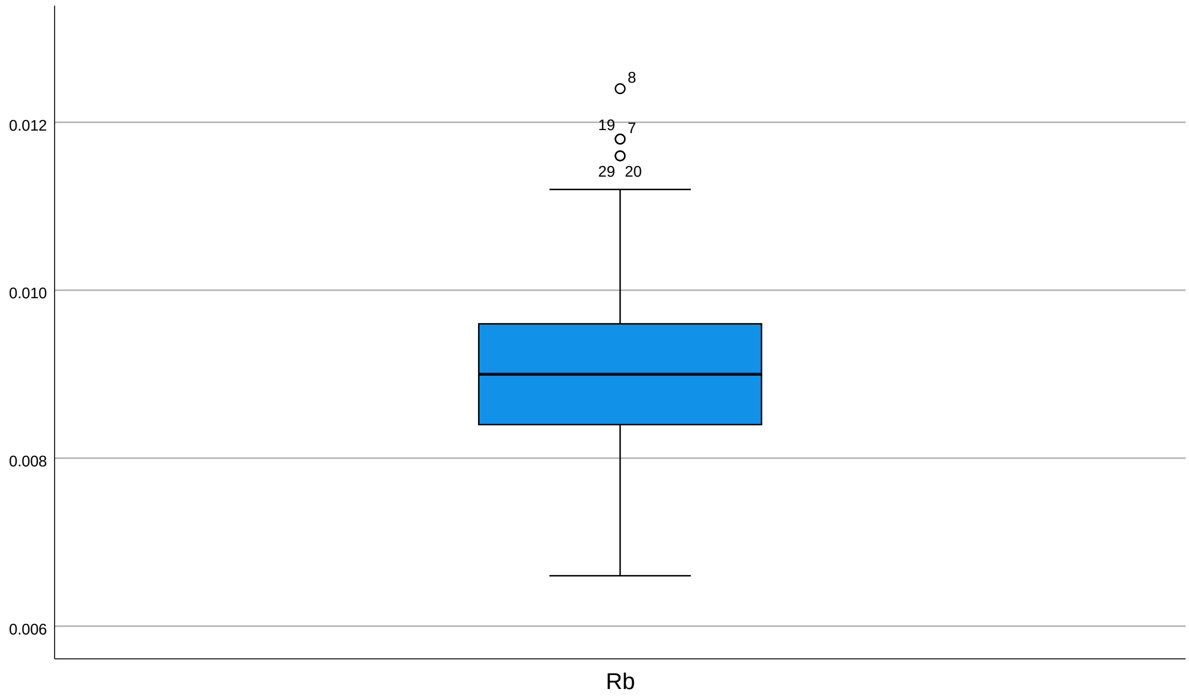
Mn



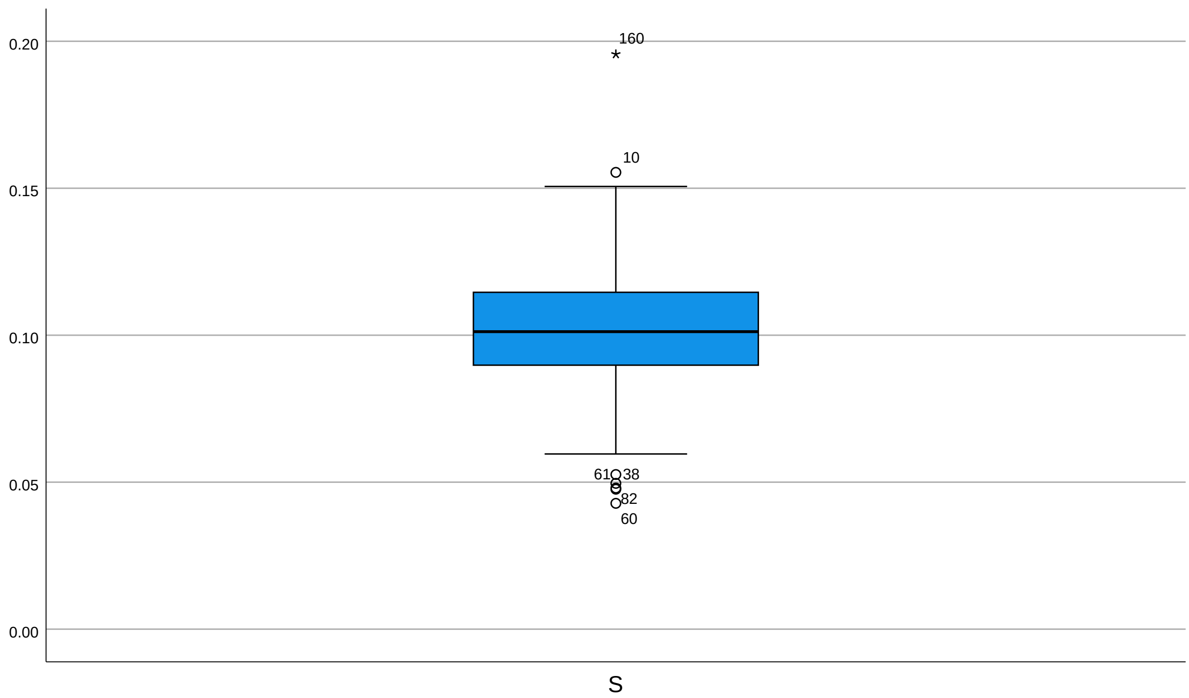
P



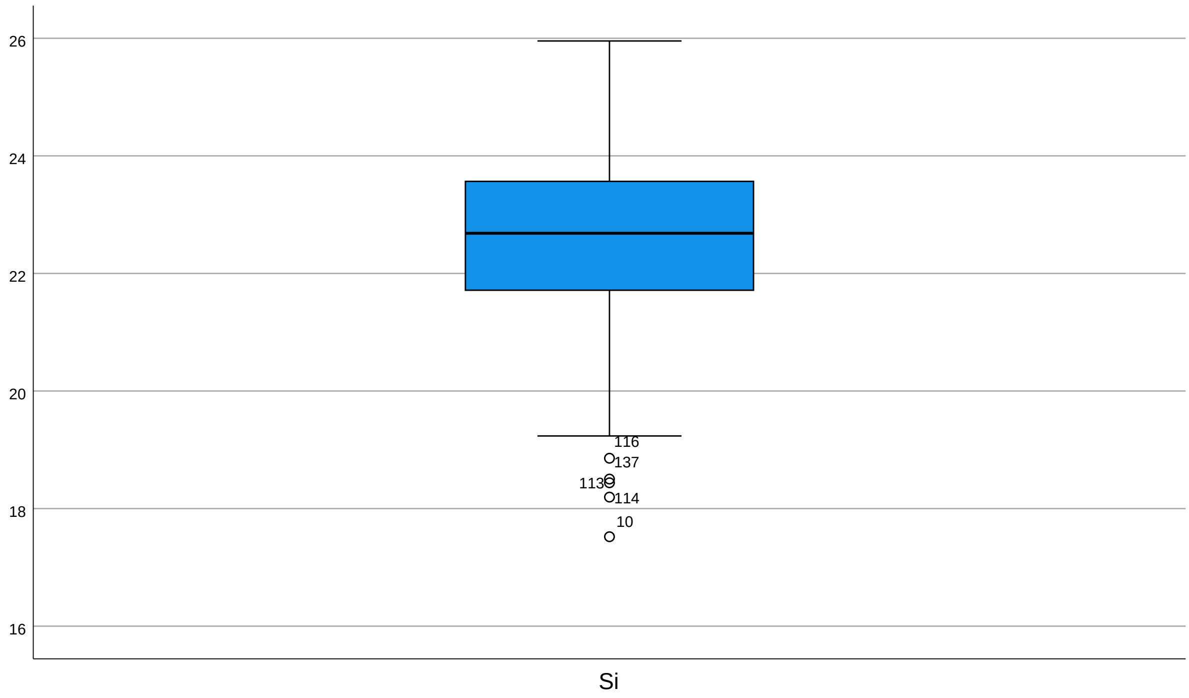
Rb


0.012
0.010
0.008
0.006
8
19
7
29
20
Rb

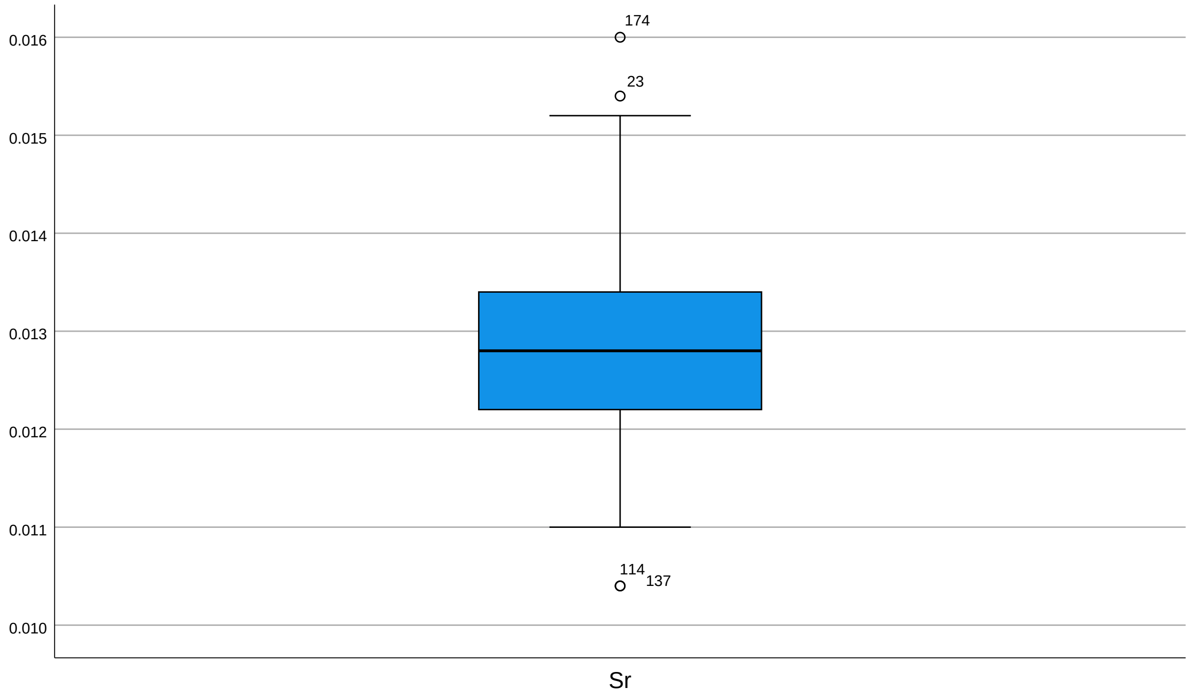
S


0.20
0.15
0.10
0.05
0.00
160
10
61
38
82
60
S

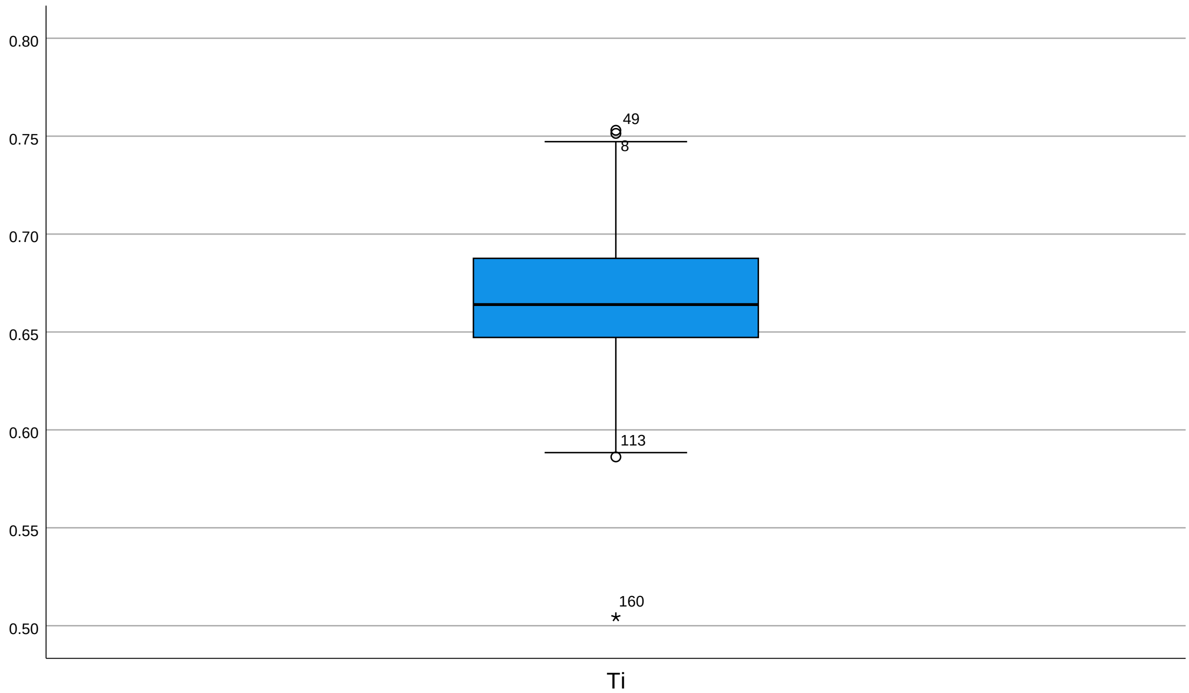
Si


26
24
22
20
18
16
116
137
113
114
10
Si

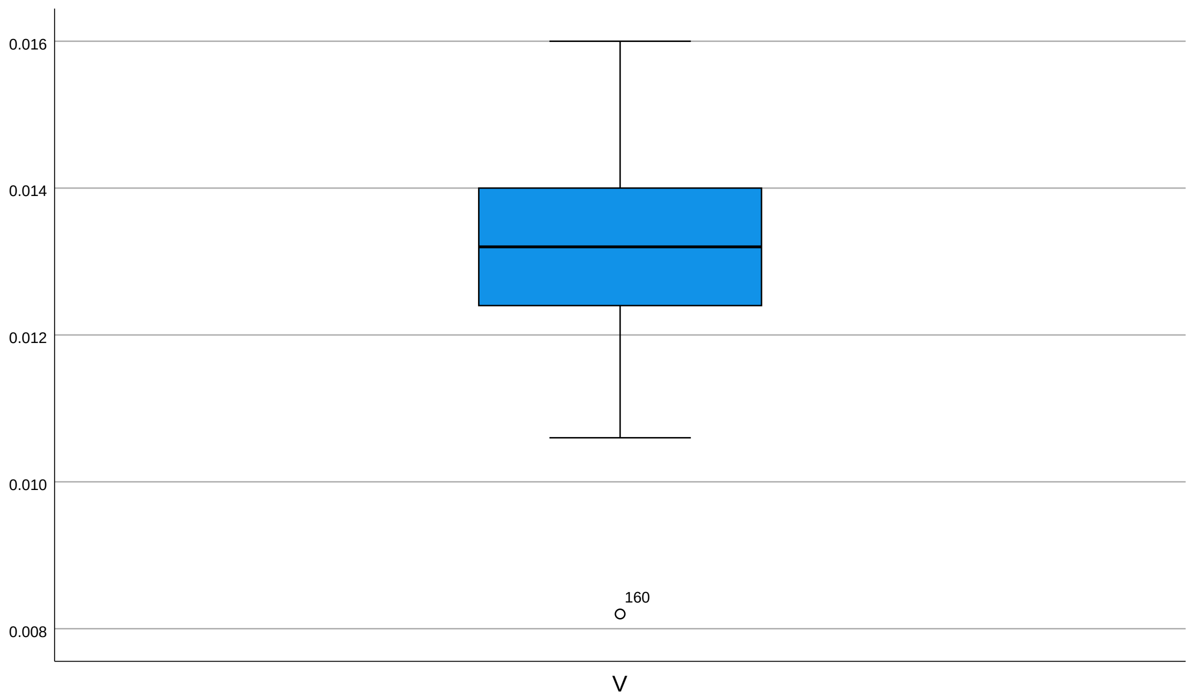
Sr


0.016
0.015
0.014
0.013
0.012
0.011
0.010
174
23
114
137
Sr

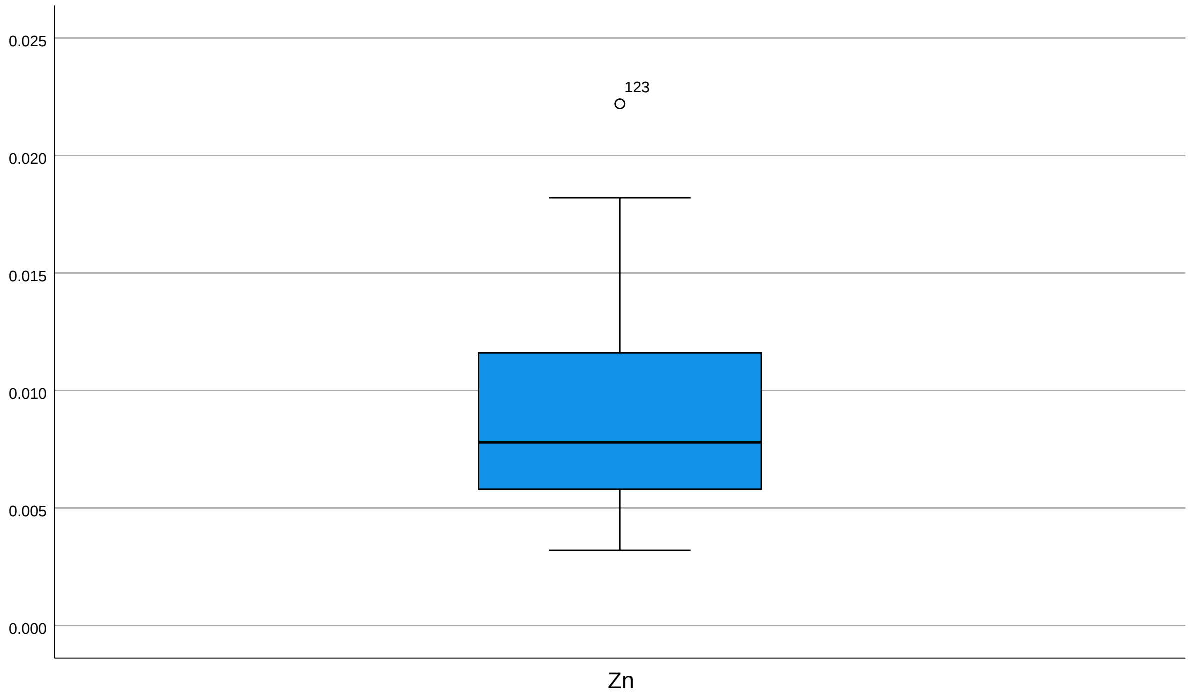
Ti


0.80
0.75
0.70
0.65
0.60
0.55
0.50
49
8
113
160
Ti

V

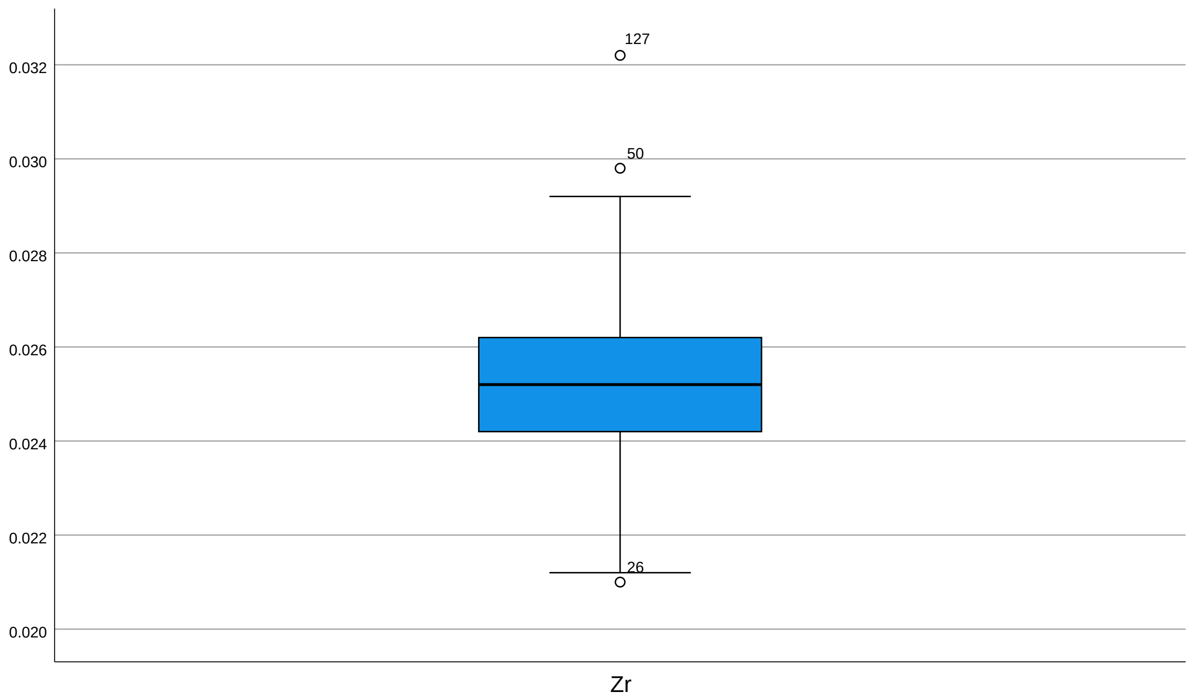

0.016
0.014
0.012
0.010
0.008
160
V

Zn



0.025
0.020
0.015
0.010
0.005
0.000
123
Zn

Zr



0.032
0.030
0.028
0.026
0.024
0.022
0.020
127
50
26
Zr

Factor Analysis

Notes

Output Created		06-NOV-2022 13:33:15
Comments		
Input	Data	C:\Users\vanes\Documents\PhD\Analysis\SPSS\Combined (Geochemical and Elements)\Combined (excluding P5).sav
	Active Dataset	DataSet3
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	179
Missing Value Handling	Definition of Missing	MISSING=EXCLUDE: User-defined missing values are treated as missing.
	Cases Used	LISTWISE: Statistics are based on cases with no missing values for any variable used.
Syntax		FACTOR /VARIABLES ZpH ZEC ZLOI ZMagSus ZAl ZBa ZCa ZCr ZFe ZK ZMn ZP ZRb ZS ZSi ZSr ZTi ZV ZZn ZZr /MISSING LISTWISE /ANALYSIS ZpH ZEC ZLOI ZMagSus ZAl ZBa ZCa ZCr ZFe ZK ZMn ZP ZRb ZS ZSi ZSr ZTi ZV ZZn ZZr /PRINT INITIAL CORRELATION SIG DET KMO EXTRACTION /PLOT EIGEN ROTATION /CRITERIA MINEIGEN (1) ITERATE(100) /EXTRACTION PC /ROTATION NOROTATE /METHOD=CORRELATIO...
Resources	Processor Time	00:00:00.16
	Elapsed Time	00:00:00.25
	Maximum Memory Required	48768 (47.625K) bytes

Correlation Matrix[a]

		Zscore(pH)	Zscore(EC)	Zscore(LOI)	Zscore (MagSus)
Correlation	Zscore(pH)	1.000	-.562	-.137	-.324
	Zscore(EC)	-.562	1.000	.379	.136
	Zscore(LOI)	-.137	.379	1.000	-.222
	Zscore(MagSus)	-.324	.136	-.222	1.000
	Zscore(Al)	.029	-.274	-.901	.326
	Zscore(Ba)	.177	-.306	-.811	.212
	Zscore(Ca)	.072	.026	-.503	.230
	Zscore(Cr)	.126	-.234	-.114	-.068
	Zscore(Fe)	.193	-.440	-.167	-.286
	Zscore(K)	.240	-.328	-.766	-.185
	Zscore(Mn)	-.150	.047	-.411	.709
	Zscore(P)	-.009	.033	.001	.041
	Zscore(Rb)	.017	.059	-.391	-.013
	Zscore(S)	-.198	.486	.881	-.077
	Zscore(Si)	-.160	.009	-.687	.462
	Zscore(Sr)	.091	-.256	-.771	.170
	Zscore(Ti)	.001	-.318	-.582	.082
	Zscore(V)	.114	-.278	-.383	-.017
	Zscore(Zn)	-.061	-.066	-.625	.636
	Zscore(Zr)	-.163	-.054	-.506	.274
Sig. (1-tailed)	Zscore(pH)		.000	.034	.000
	Zscore(EC)	.000		.000	.035
	Zscore(LOI)	.034	.000		.001
	Zscore(MagSus)	.000	.035	.001	
	Zscore(Al)	.349	.000	.000	.000
	Zscore(Ba)	.009	.000	.000	.002
	Zscore(Ca)	.168	.364	.000	.001
	Zscore(Cr)	.047	.001	.064	.183
	Zscore(Fe)	.005	.000	.013	.000
	Zscore(K)	.001	.000	.000	.007
	Zscore(Mn)	.023	.266	.000	.000
	Zscore(P)	.451	.331	.495	.291
	Zscore(Rb)	.413	.218	.000	.430
	Zscore(S)	.004	.000	.000	.153
	Zscore(Si)	.016	.454	.000	.000
	Zscore(Sr)	.114	.000	.000	.012
	Zscore(Ti)	.493	.000	.000	.137
	Zscore(V)	.064	.000	.000	.411

Correlation Matrix[a]

		Zscore(Al)	Zscore(Ba)	Zscore(Ca)	Zscore(Cr)	Zscore(Fe)
Correlation	Zscore(pH)	.029	.177	.072	.126	.193
	Zscore(EC)	-.274	-.306	.026	-.234	-.440
	Zscore(LOI)	-.901	-.811	-.503	-.114	-.167
	Zscore(MagSus)	.326	.212	.230	-.068	-.286
	Zscore(Al)	1.000	.824	.529	.156	.177
	Zscore(Ba)	.824	1.000	.474	.266	.269
	Zscore(Ca)	.529	.474	1.000	-.095	-.126
	Zscore(Cr)	.156	.266	-.095	1.000	.461
	Zscore(Fe)	.177	.269	-.126	.461	1.000
	Zscore(K)	.770	.700	.338	.233	.263
	Zscore(Mn)	.480	.490	.268	.027	-.055
	Zscore(P)	.081	.188	.180	.157	.188
	Zscore(Rb)	.418	.404	.055	.147	.053
	Zscore(S)	-.776	-.691	-.456	-.078	-.146
	Zscore(Si)	.744	.505	.531	-.132	-.379
	Zscore(Sr)	.743	.700	.463	.147	.138
	Zscore(Ti)	.594	.413	.150	.091	.148
	Zscore(V)	.357	.318	.123	.207	.344
	Zscore(Zn)	.682	.685	.468	.063	.046
	Zscore(Zr)	.556	.448	.256	-.057	.003
Sig. (1-tailed)	Zscore(pH)	.349	.009	.168	.047	.005
	Zscore(EC)	.000	.000	.364	.001	.000
	Zscore(LOI)	.000	.000	.000	.064	.013
	Zscore(MagSus)	.000	.002	.001	.183	.000
	Zscore(Al)		.000	.000	.019	.009
	Zscore(Ba)	.000		.000	.000	.000
	Zscore(Ca)	.000	.000		.104	.046
	Zscore(Cr)	.019	.000	.104		.000
	Zscore(Fe)	.009	.000	.046	.000	
	Zscore(K)	.000	.000	.000	.001	.000
	Zscore(Mn)	.000	.000	.000	.362	.234
	Zscore(P)	.139	.006	.008	.018	.006
	Zscore(Rb)	.000	.000	.230	.025	.240
	Zscore(S)	.000	.000	.000	.149	.026
	Zscore(Si)	.000	.000	.000	.039	.000
	Zscore(Sr)	.000	.000	.000	.025	.032
	Zscore(Ti)	.000	.000	.023	.113	.024
	Zscore(V)	.000	.000	.051	.003	.000

Correlation Matrix[a]

		Zscore(K)	Zscore(Mn)	Zscore(P)	Zscore(Rb)	Zscore(S)
Correlation	Zscore(pH)	.240	-.150	-.009	.017	-.198
	Zscore(EC)	-.328	.047	.033	.059	.486
	Zscore(LOI)	-.766	-.411	.001	-.391	.881
	Zscore(MagSus)	-.185	.709	.041	-.013	-.077
	Zscore(Al)	.770	.480	.081	.418	-.776
	Zscore(Ba)	.700	.490	.188	.404	-.691
	Zscore(Ca)	.338	.268	.180	.055	-.456
	Zscore(Cr)	.233	.027	.157	.147	-.078
	Zscore(Fe)	.263	-.055	.188	.053	-.146
	Zscore(K)	1.000	.062	.006	.574	-.731
	Zscore(Mn)	.062	1.000	.230	.230	-.183
	Zscore(P)	.006	.230	1.000	.141	.058
	Zscore(Rb)	.574	.230	.141	1.000	-.247
	Zscore(S)	-.731	-.183	.058	-.247	1.000
	Zscore(Si)	.464	.363	-.162	.277	-.605
	Zscore(Sr)	.632	.256	.056	.350	-.648
	Zscore(Ti)	.640	.071	-.127	.449	-.526
	Zscore(V)	.352	.094	.011	.239	-.311
	Zscore(Zn)	.277	.827	.200	.196	-.417
	Zscore(Zr)	.497	.275	-.016	.448	-.484
Sig. (1-tailed)	Zscore(pH)	.001	.023	.451	.413	.004
	Zscore(EC)	.000	.266	.331	.218	.000
	Zscore(LOI)	.000	.000	.495	.000	.000
	Zscore(MagSus)	.007	.000	.291	.430	.153
	Zscore(Al)	.000	.000	.139	.000	.000
	Zscore(Ba)	.000	.000	.006	.000	.000
	Zscore(Ca)	.000	.000	.008	.230	.000
	Zscore(Cr)	.001	.362	.018	.025	.149
	Zscore(Fe)	.000	.234	.006	.240	.026
	Zscore(K)		.206	.468	.000	.000
	Zscore(Mn)	.206		.001	.001	.007
	Zscore(P)	.468	.001		.030	.220
	Zscore(Rb)	.000	.001	.030		.000
	Zscore(S)	.000	.007	.220	.000	
	Zscore(Si)	.000	.000	.015	.000	.000
	Zscore(Sr)	.000	.000	.228	.000	.000
	Zscore(Ti)	.000	.173	.045	.000	.000
	Zscore(V)	.000	.106	.441	.001	.000

Correlation Matrix[a]

		Zscore(Si)	Zscore(Sr)	Zscore(Ti)	Zscore(V)	Zscore(Zn)
Correlation	Zscore(pH)	-.160	.091	.001	.114	-.061
	Zscore(EC)	.009	-.256	-.318	-.278	-.066
	Zscore(LOI)	-.687	-.771	-.582	-.383	-.625
	Zscore(MagSus)	.462	.170	.082	-.017	.636
	Zscore(Al)	.744	.743	.594	.357	.682
	Zscore(Ba)	.505	.700	.413	.318	.685
	Zscore(Ca)	.531	.463	.150	.123	.468
	Zscore(Cr)	-.132	.147	.091	.207	.063
	Zscore(Fe)	-.379	.138	.148	.344	.046
	Zscore(K)	.464	.632	.640	.352	.277
	Zscore(Mn)	.363	.256	.071	.094	.827
	Zscore(P)	-.162	.056	-.127	.011	.200
	Zscore(Rb)	.277	.350	.449	.239	.196
	Zscore(S)	-.605	-.648	-.526	-.311	-.417
	Zscore(Si)	1.000	.584	.459	.108	.463
	Zscore(Sr)	.584	1.000	.508	.337	.505
	Zscore(Ti)	.459	.508	1.000	.424	.192
	Zscore(V)	.108	.337	.424	1.000	.250
	Zscore(Zn)	.463	.505	.192	.250	1.000
	Zscore(Zr)	.479	.416	.578	.262	.376
Sig. (1-tailed)	Zscore(pH)	.016	.114	.493	.064	.210
	Zscore(EC)	.454	.000	.000	.000	.190
	Zscore(LOI)	.000	.000	.000	.000	.000
	Zscore(MagSus)	.000	.012	.137	.411	.000
	Zscore(Al)	.000	.000	.000	.000	.000
	Zscore(Ba)	.000	.000	.000	.000	.000
	Zscore(Ca)	.000	.000	.023	.051	.000
	Zscore(Cr)	.039	.025	.113	.003	.201
	Zscore(Fe)	.000	.032	.024	.000	.269
	Zscore(K)	.000	.000	.000	.000	.000
	Zscore(Mn)	.000	.000	.173	.106	.000
	Zscore(P)	.015	.228	.045	.441	.004
	Zscore(Rb)	.000	.000	.000	.001	.004
	Zscore(S)	.000	.000	.000	.000	.000
	Zscore(Si)		.000	.000	.074	.000
	Zscore(Sr)	.000		.000	.000	.000
	Zscore(Ti)	.000	.000		.000	.005
	Zscore(V)	.074	.000	.000		.000

Correlation Matrix[a]

		Zscore(Zr)
Correlation	Zscore(pH)	-.163
	Zscore(EC)	-.054
	Zscore(LOI)	-.506
	Zscore(MagSus)	.274
	Zscore(Al)	.556
	Zscore(Ba)	.448
	Zscore(Ca)	.256
	Zscore(Cr)	-.057
	Zscore(Fe)	.003
	Zscore(K)	.497
	Zscore(Mn)	.275
	Zscore(P)	-.016
	Zscore(Rb)	.448
	Zscore(S)	-.484
	Zscore(Si)	.479
	Zscore(Sr)	.416
	Zscore(Ti)	.578
	Zscore(V)	.262
	Zscore(Zn)	.376
	Zscore(Zr)	1.000
Sig. (1-tailed)	Zscore(pH)	.015
	Zscore(EC)	.238
	Zscore(LOI)	.000
	Zscore(MagSus)	.000
	Zscore(Al)	.000
	Zscore(Ba)	.000
	Zscore(Ca)	.000
	Zscore(Cr)	.226
	Zscore(Fe)	.485
	Zscore(K)	.000
	Zscore(Mn)	.000
	Zscore(P)	.416
	Zscore(Rb)	.000
	Zscore(S)	.000
	Zscore(Si)	.000
	Zscore(Sr)	.000
	Zscore(Ti)	.000
	Zscore(V)	.000

Correlation Matrix[a]

	Zscore(pH)	Zscore(EC)	Zscore(LOI)	Zscore (MagSus)
Zscore(Zn)	.210	.190	.000	.000
Zscore(Zr)	.015	.238	.000	.000

Correlation Matrix[a]

	Zscore(Al)	Zscore(Ba)	Zscore(Ca)	Zscore(Cr)	Zscore(Fe)
Zscore(Zn)	.000	.000	.000	.201	.269
Zscore(Zr)	.000	.000	.000	.226	.485

Correlation Matrix[a]

	Zscore(K)	Zscore(Mn)	Zscore(P)	Zscore(Rb)	Zscore(S)
Zscore(Zn)	.000	.000	.004	.004	.000
Zscore(Zr)	.000	.000	.416	.000	.000

Correlation Matrix[a]

	Zscore(Si)	Zscore(Sr)	Zscore(Ti)	Zscore(V)	Zscore(Zn)
Zscore(Zn)	.000	.000	.005	.000	
Zscore(Zr)	.000	.000	.000	.000	.000

Correlation Matrix[a]

	Zscore(Zr)
Zscore(Zn)	.000
Zscore(Zr)	

a. Determinant = 1.36E-008

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.820
Bartlett's Test of Sphericity	Approx. Chi-Square	3087.933
	df	190
	Sig.	.000

Communalities

	Initial	Extraction
Zscore(pH)	1.000	.625
Zscore(EC)	1.000	.788
Zscore(LOI)	1.000	.916
Zscore(MagSus)	1.000	.860
Zscore(Al)	1.000	.913
Zscore(Ba)	1.000	.836
Zscore(Ca)	1.000	.687
Zscore(Cr)	1.000	.497
Zscore(Fe)	1.000	.733
Zscore(K)	1.000	.893
Zscore(Mn)	1.000	.835
Zscore(P)	1.000	.711
Zscore(Rb)	1.000	.699
Zscore(S)	1.000	.827
Zscore(Si)	1.000	.848
Zscore(Sr)	1.000	.673
Zscore(Ti)	1.000	.751
Zscore(V)	1.000	.447
Zscore(Zn)	1.000	.885
Zscore(Zr)	1.000	.627

Extraction Method: Principal Component Analysis.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared ..	
	Total	% of Variance	Cumulative %	Total	% of Variance
1	7.625	38.125	38.125	7.625	38.125
2	2.984	14.920	53.045	2.984	14.920
3	1.861	9.305	62.350	1.861	9.305
4	1.448	7.238	69.589	1.448	7.238
5	1.132	5.658	75.246	1.132	5.658
6	.814	4.070	79.317		
7	.789	3.946	83.263		
8	.664	3.319	86.582		
9	.548	2.738	89.319		
10	.450	2.249	91.569		
11	.356	1.779	93.348		
12	.325	1.626	94.974		
13	.232	1.162	96.136		
14	.189	.946	97.082		
15	.157	.784	97.866		
16	.140	.698	98.564		
17	.117	.584	99.148		
18	.087	.435	99.583		
19	.051	.256	99.838		
20	.032	.162	100.000		

Total Variance Explained

Component	Extraction Sums .. Cumulative %
1	38.125
2	53.045
3	62.350
4	69.589
5	75.246
6	
7	
8	
9	
10	
11	
12	
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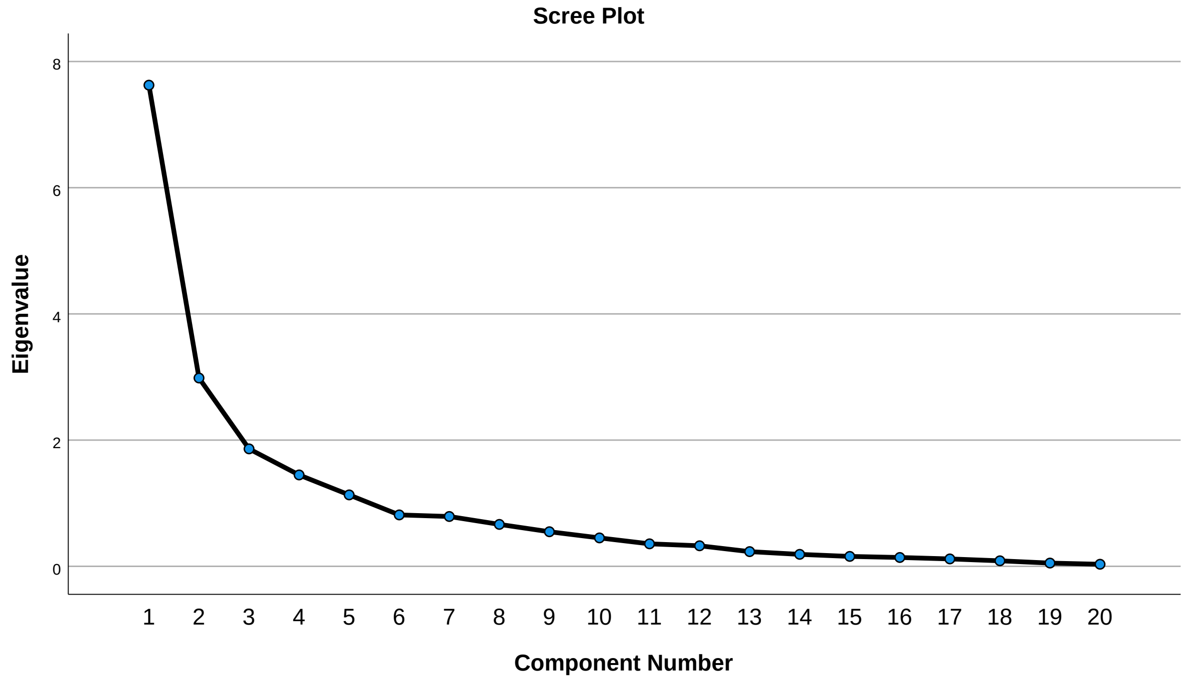
16	
17	
18	
19	
20	

Extraction Method: Principal Component Analysis.



Component Matrix[a]

	Component				
	1	2	3	4	5
Zscore(pH)	.097	-.575	.106	-.509	.120
Zscore(EC)	-.335	.619	-.139	.397	.340
Zscore(LOI)	-.944	.059	.054	.135	.011
Zscore(MagSus)	.316	.743	.256	-.036	-.376
Zscore(Al)	.954	.048	.010	-.016	.015
Zscore(Ba)	.871	-.063	.234	-.053	.127
Zscore(Ca)	.550	.264	-.004	-.372	.420
Zscore(Cr)	.168	-.421	.470	.256	-.070
Zscore(Fe)	.168	-.649	.479	.181	-.146
Zscore(K)	.793	-.388	-.222	.126	.219
Zscore(Mn)	.490	.564	.501	.035	-.159
Zscore(P)	.078	.036	.602	.180	.556
Zscore(Rb)	.490	-.081	-.118	.601	.276
Zscore(S)	-.829	.192	.186	.261	.012
Zscore(Si)	.717	.415	-.378	-.137	.004
Zscore(Sr)	.808	-.060	-.050	-.064	.096
Zscore(Ti)	.656	-.215	-.358	.297	-.241
Zscore(V)	.439	-.322	.100	.221	-.302
Zscore(Zn)	.698	.428	.440	-.091	-.109
Zscore(Zr)	.635	.142	-.262	.353	-.104

Cluster

Notes

Output Created		06-NOV-2022 13:39:26
Comments		
Input	Data	C:\Users\vanes\Documents\PhD\Analysis\SPSS\Combined (Geochemical and Elements)\Combined (excluding P5).sav
	Active Dataset	DataSet3
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	179
Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any variable used.
Syntax		CLUSTER ZpH ZEC ZLOI ZMagSus ZAl ZBa ZCa ZCr ZFe ZK ZMn ZP ZRb ZS ZSi ZSr ZTi ZV ZZn ZZr /METHOD WARD /MEASURE=SEUCLID /PRINT SCHEDULE /PLOT DENDROGRAM VICICLE.
Resources	Processor Time	00:00:00.33
	Elapsed Time	00:00:00.37

Case Processing Summary[a,b]

Cases					
Valid		Missing		Total	
N	Percent	N	Percent	N	Percent
179	100.0	0	.0	179	100.0

a. Squared Euclidean Distance used

b. Ward Linkage

Ward Linkage

Agglomeration Schedule

Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	87	90	1.431	0	0	10
2	5	7	3.158	0	0	54
3	75	120	4.892	0	0	32
4	17	37	6.662	0	0	100
5	92	93	8.498	0	0	28
6	72	85	10.364	0	0	66
7	121	149	12.337	0	0	39
8	27	55	14.351	0	0	77
9	147	148	16.393	0	0	55
10	87	89	18.469	1	0	102
11	176	177	20.603	0	0	43
12	71	77	22.758	0	0	83
13	76	78	24.931	0	0	32
14	163	164	27.182	0	0	36
15	18	29	29.476	0	0	67
16	94	102	31.777	0	0	48
17	155	156	34.139	0	0	138
18	79	99	36.521	0	0	79
19	80	100	38.917	0	0	88
20	73	86	41.357	0	0	56
21	54	170	43.841	0	0	24
22	42	56	46.350	0	0	76
23	28	46	49.066	0	0	70
24	54	168	51.802	21	0	104
25	8	20	54.545	0	0	111
26	53	178	57.341	0	0	112
27	84	179	60.177	0	0	56
28	92	101	63.043	5	0	125
29	1	14	65.913	0	0	113
30	154	174	68.848	0	0	116
31	22	47	71.819	0	0	86
32	75	76	74.798	3	13	87
33	118	119	77.882	0	0	65
34	3	161	80.984	0	0	105
35	138	160	84.154	0	0	130
36	163	165	87.405	14	0	150
37	31	109	90.718	0	0	72

Agglomeration Schedule

Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
38	12	157	94.035	0	0	82
39	97	121	97.421	0	7	66
40	70	111	100.869	0	0	97
41	33	115	104.347	0	0	93
42	15	140	107.837	0	0	120
43	175	176	111.333	0	11	112
44	117	169	114.887	0	0	93
45	110	133	118.493	0	0	103
46	143	144	122.146	0	0	98
47	36	141	125.836	0	0	81
48	94	126	129.530	16	0	91
49	98	122	133.281	0	0	78
50	44	112	137.137	0	0	100
51	52	64	141.006	0	0	107
52	24	59	144.912	0	0	153
53	25	57	148.822	0	0	105
54	4	5	152.837	0	2	94
55	146	147	156.878	0	9	129
56	73	84	161.077	20	27	85
57	11	137	165.292	0	0	134
58	135	159	169.515	0	0	97
59	32	107	173.742	0	0	101
60	82	83	178.082	0	0	99
61	21	51	182.486	0	0	111
62	105	129	186.905	0	0	106
63	43	134	191.380	0	0	145
64	2	45	195.872	0	0	139
65	65	118	200.507	0	33	108
66	72	97	205.275	6	39	87
67	18	30	210.047	15	0	117
68	116	139	214.936	0	0	154
69	38	60	219.838	0	0	144
70	6	28	224.778	0	23	128
71	172	173	229.803	0	0	129
72	31	131	234.908	37	0	127
73	74	152	240.068	0	0	92
74	128	130	245.270	0	0	109

Agglomeration Schedule

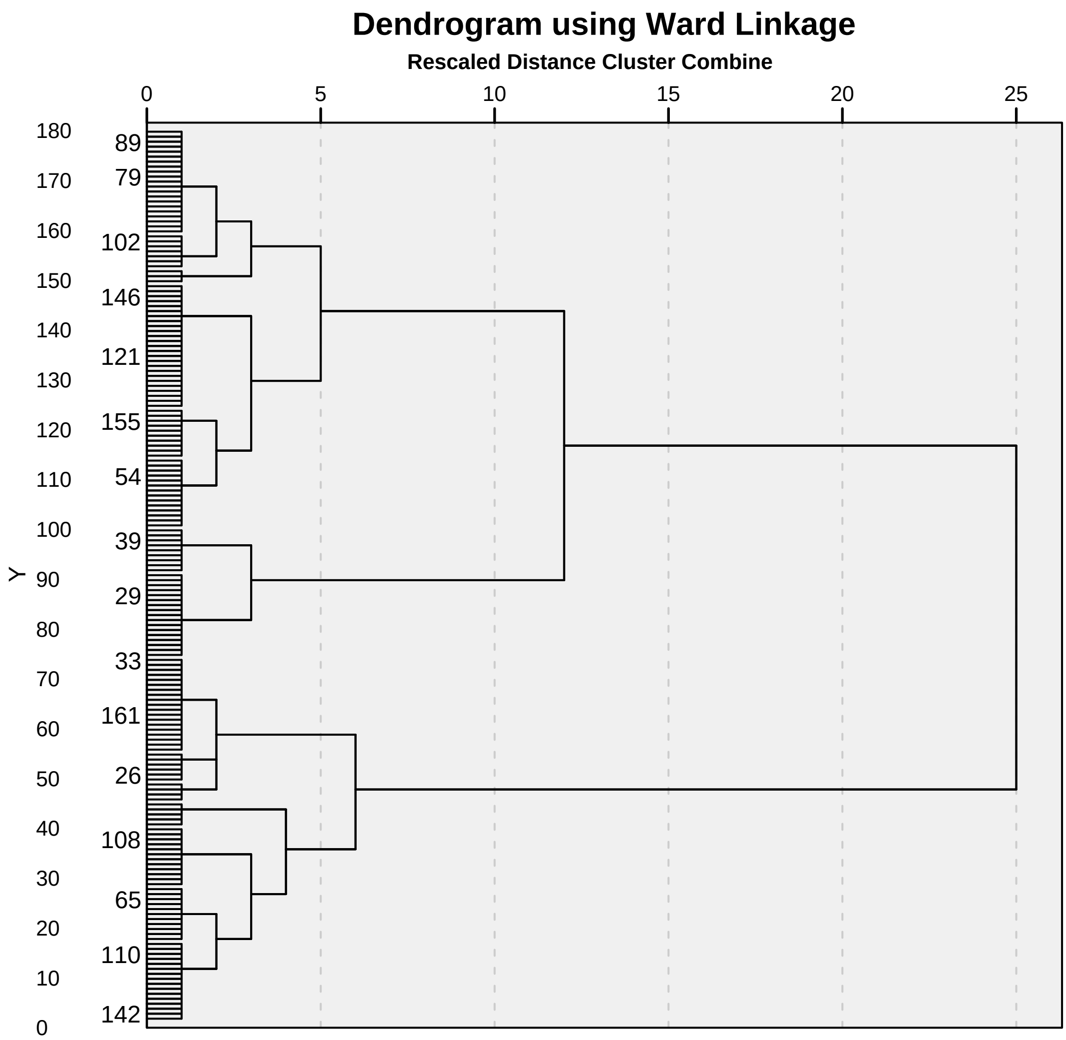
Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
75	26	35	250.516	0	0	113
76	16	42	255.775	0	22	132
77	27	34	261.047	8	0	120
78	98	104	266.410	49	0	119
79	79	88	271.817	18	0	123
80	48	58	277.232	0	0	141
81	36	142	282.704	47	0	118
82	12	158	288.209	38	0	103
83	71	91	293.793	12	0	102
84	10	113	299.402	0	0	114
85	73	153	305.270	56	0	96
86	22	62	311.262	31	0	140
87	72	75	317.255	66	32	131
88	41	80	323.297	0	19	125
89	13	162	329.406	0	0	154
90	166	167	335.522	0	0	136
91	94	103	341.679	48	0	124
92	74	150	347.859	73	0	149
93	33	117	354.057	41	44	142
94	4	19	360.290	54	0	117
95	49	50	366.562	0	0	152
96	73	96	372.884	85	0	116
97	70	135	379.257	40	58	110
98	143	145	385.768	46	0	147
99	39	82	392.339	0	60	115
100	17	44	398.940	4	50	130
101	9	32	405.604	0	59	128
102	71	87	412.280	83	10	119
103	12	110	419.118	82	45	145
104	54	171	426.051	24	0	132
105	3	25	433.217	34	53	146
106	105	108	440.431	62	0	126
107	52	63	448.106	51	0	127
108	65	66	455.805	65	0	121
109	106	128	463.522	0	74	126
110	69	70	471.445	0	97	135
111	8	21	479.401	25	61	143

Agglomeration Schedule

Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
112	53	175	487.483	26	43	136
113	1	26	495.761	29	75	139
114	10	114	504.125	84	0	134
115	39	81	512.713	99	0	158
116	73	154	521.321	96	30	131
117	4	18	530.014	94	67	133
118	36	67	538.996	81	0	141
119	71	98	548.146	102	78	123
120	15	27	557.357	42	77	146
121	65	68	566.790	108	0	157
122	95	124	576.857	0	0	155
123	71	79	587.476	119	79	156
124	94	127	598.125	91	0	151
125	41	92	609.189	88	28	149
126	105	106	620.278	106	109	160
127	31	52	631.395	72	107	160
128	6	9	642.558	70	101	138
129	146	172	653.950	55	71	161
130	17	138	665.508	100	35	142
131	72	73	677.523	87	116	147
132	16	54	689.681	76	104	162
133	4	132	702.133	117	0	140
134	10	11	715.210	114	57	174
135	69	136	728.482	110	0	157
136	53	166	741.823	112	90	162
137	123	151	755.572	0	0	151
138	6	155	769.576	128	17	153
139	1	2	783.637	113	64	165
140	4	22	798.225	133	86	163
141	36	48	812.913	118	80	150
142	17	33	828.178	130	93	159
143	8	40	844.676	111	0	148
144	38	61	861.506	69	0	152
145	12	43	878.466	103	63	164
146	3	15	896.315	105	120	159
147	72	143	914.164	131	98	161
148	8	23	932.113	143	0	163

Agglomeration Schedule

Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
149	41	74	951.113	125	92	156
150	36	163	971.716	141	36	164
151	94	123	992.373	124	137	169
152	38	49	1013.324	144	95	158
153	6	24	1034.412	138	52	167
154	13	116	1055.655	89	68	165
155	95	125	1076.960	122	0	172
156	41	71	1099.749	149	123	169
157	65	69	1123.326	121	135	168
158	38	39	1148.174	152	115	173
159	3	17	1174.899	146	142	166
160	31	105	1201.756	127	126	170
161	72	146	1229.633	147	129	171
162	16	53	1259.028	132	136	167
163	4	8	1290.968	140	148	173
164	12	36	1324.050	145	150	168
165	1	13	1360.572	139	154	166
166	1	3	1398.677	165	159	176
167	6	16	1447.703	153	162	171
168	12	65	1498.177	164	157	170
169	41	94	1549.151	156	151	172
170	12	31	1619.761	168	160	174
171	6	72	1697.926	167	161	175
172	41	95	1783.995	169	155	175
173	4	38	1873.520	163	158	177
174	10	12	1985.124	134	170	176
175	6	41	2152.554	171	172	177
176	1	10	2327.586	166	174	178
177	4	6	2715.366	173	175	178
178	1	4	3560.000	176	177	0



Dendrogram using Ward Linkage
Rescaled Distance Cluster Combine
0
5
10
15
20
25
Y
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
89
79
102
146
121
155
54
39
29
33
161
26
108
65
110
142

Hierarchical Cluster Analysis (10/07/2022 16:35:48)

Notes

X-Function	Hierarchical Cluster Analysis
User Name	vanes
Time	10/07/2022 16:35:48
Data Filter	No

Input Data

Variable

	Data	Range
pH	[Book1]ZScores!C"pH"	[1*:179*]
EC	[Book1]ZScores!D"EC"	[1*:179*]
LOI	[Book1]ZScores!E"LOI"	[1*:179*]
MagSus	[Book1]ZScores!F"MagSus"	[1*:179*]
Al	[Book1]ZScores!G"Al"	[1*:179*]
Ba	[Book1]ZScores!H"Ba"	[1*:179*]
Ca	[Book1]ZScores!I"Ca"	[1*:179*]
Cr	[Book1]ZScores!J"Cr"	[1*:179*]
Fe	[Book1]ZScores!K"Fe"	[1*:179*]
K	[Book1]ZScores!L"K"	[1*:179*]
Mn	[Book1]ZScores!M"Mn"	[1*:179*]
P	[Book1]ZScores!N"P"	[1*:179*]
Rb	[Book1]ZScores!O"Rb"	[1*:179*]
S	[Book1]ZScores!P"S"	[1*:179*]
Si	[Book1]ZScores!Q"Si"	[1*:179*]
Sr	[Book1]ZScores!R"Sr"	[1*:179*]
Ti	[Book1]ZScores!S"Ti"	[1*:179*]
V	[Book1]ZScores!T"V"	[1*:179*]
Zn	[Book1]ZScores!U"Zn"	[1*:179*]
Zr	[Book1]ZScores!V"Zr"	[1*:179*]

Descriptive Statistics

	N analysis	N missing	Mean	Standard Deviation	Sum	Minimum	Median	Maximum
pH	179	0	1.28492E-6	1	2.3E-4	-1.91914	-0.29873	4.15738
EC	179	0	5.58659E-7	1	1E-4	-2.05095	-0.13953	2.53543
LOI	179	0	5.58659E-8	1	1E-5	-2.4217	-0.06759	3.00169
MagSus	179	0	-1.67598E-7	1	-3E-5	-1.15586	-0.40725	3.78722
Al	179	0	5.58659E-8	1	1E-5	-2.10047	0.01196	2.98921
Ba	179	0	3.35196E-7	1	6E-5	-2.28015	-0.13557	3.16595
Ca	179	0	1.67598E-7	1	3E-5	-2.15594	-0.05531	7.41963
Cr	179	0	-5.58659E-8	1	-1E-5	-2.47497	-0.1136	3.03489
Fe	179	0	5.58659E-8	1	1E-5	-2.95913	-0.07391	3.62035
K	179	0	4.46927E-7	1	8E-5	-2.22979	-0.16973	3.65149
Mn	179	0	-1.02339E-16	1	-1.83187E-14	-1.16565	-0.25382	3.60061
P	179	0	5.58659E-8	1	1E-5	-2.03549	-0.18613	3.89622
Rb	179	0	-6.70391E-7	1	-1.2E-4	-2.14068	-0.10248	3.36246
S	179	0	5.58659E-8	1	1E-5	-2.93619	-0.0098	2.70613
Si	179	0	-5.58659E-8	1	-1E-5	-3.23895	0.06035	2.13112
Sr	179	0	1.67598E-7	1	3E-5	-2.59816	-0.03461	3.38346
Ti	179	0	2.23464E-7	1	4E-5	-2.52788	-0.09191	2.68135
V	179	0	-3.35196E-7	1	-6E-5	-2.23228	-0.01619	2.37036
Zn	179	0	-5.02793E-7	1	-9E-5	-1.49157	-0.27437	3.53601
Zr	179	0	-8.83837E-18	1	-1.58207E-15	-2.54821	-0.08961	4.00807

Cluster Stages

Stage	Distance	Cluster1	Cluster2	Number of Clusters	New Cluster	Next Stage
1	0.11857	3	14	19	3	12
2	0.1727	11	19	18	11	6
3	0.17608	5	6	17	5	4
4	0.29515	5	10	16	5	5
5	0.34493	5	16	15	5	11
6	0.379	4	11	14	4	17
7	0.42219	17	20	13	17	10
8	0.46944	7	15	12	7	11
9	0.53918	8	9	11	8	14
10	0.59456	13	17	10	13	13
11	0.71502	5	7	9	5	16
12	0.71683	2	3	8	2	19
13	0.78329	13	18	7	13	16
14	0.92389	8	12	6	8	15
15	0.97944	1	8	5	1	18
16	1.10133	5	13	4	5	17
17	1.79456	4	5	3	4	18
18	2.27426	1	4	2	1	19
19	4.32516	1	2	1	1	--

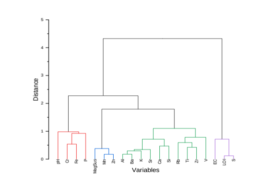
Cluster method: Ward
Distance type: Correlation

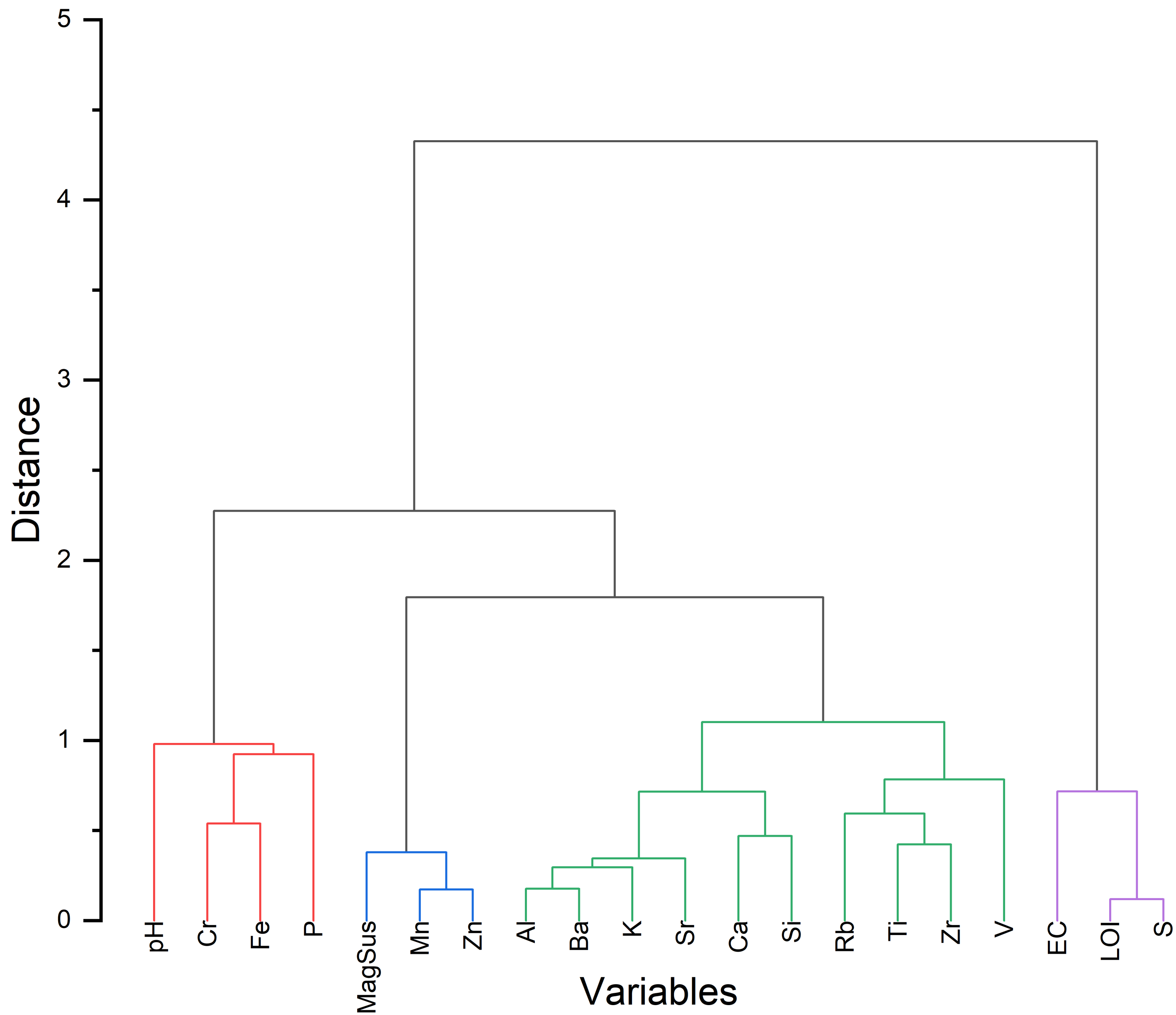
Clustroid Info

Cluster	Most Representative Variable	Least Representative Variable
1	Fe	pH
2	Mn	MagSus
3	Al	V
4	S	EC

Method: Sum of distances

Dendrogram





Distance
0
1
2
3
4
5
pH
Cr
Fe
P
MagSus
Mn
Zn
Al
Ba
K
Sr
Ca
Si
Rb
Ti
Zr
V
EC
LOI
S
Variables

K-Means Cluster Analysis (09/07/2022 15:18:34)

Initial Cluster Center

	pH	EC	LOI	MagSus	Al	Ba	Ca	Cr	Fe	K	Mn	P	Rb	S	Si	Sr	Ti	V	Zn	Zr
Cluster1	-1.10894	-0.87745	-0.39538	3.78722	0.58888	0.85206	-0.72665	1.46065	0.58354	-1.3429	3.60061	1.00414	-0.10248	0.16057	-0.15031	0.17902	-0.85393	-1.20947	1.73667	-1.02622
Cluster2	2.53697	-1.81523	1.86934	-1.05959	-1.72126	-0.98212	-1.46295	0.67353	-1.49428	-0.27077	-1.13232	-0.5665	-1.12158	1.75405	-1.69049	-1.31639	0.11421	0.49521	-1.27988	-1.26037
Cluster3	0.10637	0.60351	-0.75296	1.98446	1.15736	1.5293	7.41963	-0.63835	0.22598	0.19373	1.91504	3.89622	-0.51012	-0.58105	0.54967	0.17902	-0.348	-0.69806	2.42465	0.3787
Cluster4	0.10637	-0.85696	-1.22974	-0.84075	1.52835	2.40406	-0.30435	2.24777	3.62035	1.9184	0.46993	3.16828	1.52808	-0.57102	-0.79259	2.74257	2.45024	2.1999	1.26037	0.49578

Final Cluster Center

	pH	EC	LOI	MagSus	Al	Ba	Ca	Cr	Fe	K	Mn	P	Rb	S	Si	Sr	Ti	V	Zn	Zr
Cluster1	-0.44265	0.54404	-0.01309	0.30209	0.03852	-0.18793	0.03051	-0.27586	-0.46517	-0.08367	5.41974E-4	-0.1964	0.06916	0.10044	0.41899	0.10594	0.10846	-0.18217	-0.03831	0.08139
Cluster2	0.4121	-0.19716	1.0136	-0.78072	-1.06833	-0.85913	-0.60781	-0.00221	0.2251	-0.68236	-0.75719	-0.11449	-0.64856	0.76075	-1.07251	-0.89316	-0.72394	-0.3121	-0.91243	-0.80311
Cluster3	-0.15783	-0.31287	-0.68041	1.56443	0.78501	0.92936	0.78363	0.12026	-0.00404	-0.21244	1.8018	0.34749	-0.29744	-0.38584	0.55111	0.37407	0.08081	0.51004	1.74127	0.44487
Cluster4	0.57148	-0.87783	-1.37322	-0.65047	1.31996	1.42374	0.4397	0.67838	0.87096	1.75593	-0.05005	0.48157	1.33181	-1.44738	0.45646	1.1364	1.04696	0.69094	0.41558	0.96842

Cluster Summary

	Number of Observations	Within Cluster Sum of Square	Average Distance	Maximum Distance
Cluster1	76	733.088	3.03541	4.37349
Cluster2	53	725.62371	3.59592	5.65623
Cluster3	23	288.92812	3.30268	7.82702
Cluster4	27	345.51504	3.43922	5.43126

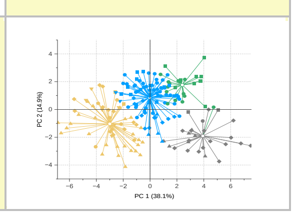
Distance between Final

	Cluster1	Cluster2	Cluster3	Cluster4
Cluster1	0	3.67565	3.65959	4.94428
Cluster2	3.67565	0	6.31906	7.08484
Cluster3	3.65959	6.31906	0	4.7596
Cluster4	4.94428	7.08484	4.7596	0

ANOVA

	Cluster DF	Cluster SS	Error DF	Error SS	F Value	Prob>F
pH	3	11.09444	175	0.82695	13.41606	6.38477E-8
EC	3	15.87069	175	0.74507	21.30083	8.26137E-12
LOI	3	38.67581	175	0.35413	109.21389	6.90875E-40
MagSus	3	35.65188	175	0.40597	87.81943	1.0314E-34
Al	3	40.6063	175	0.32103	126.48563	1.32277E-43
Ba	3	38.79949	175	0.35201	110.22322	4.09116E-40
Ca	3	12.99818	175	0.79432	16.36398	2.03066E-9
Cr	3	6.18058	175	0.91119	6.78296	2.36484E-4
Fe	3	13.20426	175	0.79078	16.69768	1.38517E-9
K	3	36.49874	175	0.39145	93.23978	4.31132E-36
Mn	3	35.04132	175	0.41643	84.14612	9.48515E-34
P	3	4.22166	175	0.94477	4.46845	0.00474
Rb	3	24.19408	175	0.60238	40.16384	8.45627E-20
S	3	30.47564	175	0.4947	61.60393	3.10583E-27
Si	3	28.97259	175	0.52047	55.66623	2.5757E-25
Sr	3	27.07299	175	0.55304	48.95329	5.04437E-23
Ti	3	19.47215	175	0.68333	28.49578	4.70772E-15
V	3	8.85248	175	0.86539	10.22952	3.05853E-6
Zn	3	39.5448	175	0.33923	116.57124	1.62573E-41
Zr	3	21.52041	175	0.64822	33.19916	4.88899E-17

Cluster Plot



Burghead Upper Surface

Outliers

Factor Analysis

Outliers

Notes

Output Created		06-NOV-2022 14:49:52
Comments		
Input	Data	C:\Users\vanes\Documents\PhD\Analysis\SPSS\Combined (Geochemical and Elements)\105.sav
	Active Dataset	DataSet4
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	N of Rows in Working Data File	96
Missing Value Handling	Definition of Missing	User-defined missing values for dependent variables are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any dependent variable or factor used.
Syntax		EXAMINE VARIABLES=pH EC LOI MagSus Al Ba Ca Cr Fe K P Rb S Si Sr Ti Zr /PLOT BOXPLOT /COMPARE GROUPS /STATISTICS DESCRIPTIVES EXTREME /CINTERVAL 95 /MISSING LISTWISE...
Resources	Processor Time	00:00:03.80
	Elapsed Time	00:00:04.49

Extreme Values

			Case Number	Value
pH	Highest	1	35	7.4
		2	21	7.4
		3	34	7.4
		4	31	7.4
		5	30	7.4
	Lowest	1	15	6.7
		2	5	6.8
		3	28	6.8
		4	22	6.8
		5	78	6.9[a]
EC	Highest	1	10	711.0
		2	15	448.0
		3	12	411.0
		4	41	387.0
		5	4	384.0
	Lowest	1	82	60.0
		2	84	69.0
		3	36	73.0
		4	46	76.0
		5	69	78.0[b]
LOI	Highest	1	4	14.5
		2	10	14.2
		3	12	11.6
		4	7	11.4
		5	13	9.6
	Lowest	1	78	.5
		2	80	.5
		3	82	.5
		4	50	.5
		5	79	.6
MagSus	Highest	1	13	384.6
		2	14	292.6
		3	4	257.5
		4	10	248.9
		5	22	182.9
	Lowest	1	78	2.7
		2	50	3.6
		3	79	4.9

Extreme Values

			Case Number	Value
		4	82	5.3
		5	46	5.3
Al	Highest	1	10	12.25
		2	13	8.56
		3	1	7.80
		4	12	6.40
		5	4	6.19
	Lowest	1	46	1.92
		2	59	1.97
		3	57	2.01
		4	34	2.09
		5	61	2.11
Ba	Highest	1	12	.047
		2	4	.046
		3	10	.045
		4	27	.044
		5	14	.043
	Lowest	1	79	.019
		2	62	.021
		3	72	.021
		4	57	.023
		5	54	.024[c]
Ca	Highest	1	4	3.50
		2	1	3.30
		3	13	2.70
		4	10	2.53
		5	12	2.26
	Lowest	1	46	.25
		2	28	.28
		3	34	.28
		4	80	.29
		5	84	.29
Cr	Highest	1	10	.017
		2	13	.012
		3	4	.012
		4	7	.011
		5	12	.010[d]

Extreme Values

			Case Number	Value
	Lowest	1	70	.002
		2	57	.002
		3	46	.002
		4	28	.002
		5	47	.002[e]
Fe	Highest	1	10	4.24
		2	13	2.86
		3	4	2.84
		4	12	2.62
		5	14	2.36
	Lowest	1	46	.17
		2	80	.20
		3	50	.21
		4	88	.23
		5	28	.23
K	Highest	1	50	1.47
		2	30	1.35
		3	38	1.34
		4	74	1.31
		5	71	1.31
	Lowest	1	10	.43
		2	4	.52
		3	12	.59
		4	13	.61
		5	7	.67
P	Highest	1	39	.39
		2	10	.37
		3	13	.35
		4	61	.26
		5	1	.26
	Lowest	1	46	.04
		2	57	.06
		3	38	.07
		4	82	.07
		5	78	.07
Rb	Highest	1	50	.0052
		2	48	.0050
		3	38	.0046

Extreme Values

			Case Number	Value
		4	40	.0046
		5	53	.0046
	Lowest	1	91	.0032
		2	62	.0032
		3	10	.0032
		4	92	.0034
		5	89	.0034[f]
S	Highest	1	12	.562
		2	4	.440
		3	7	.373
		4	13	.255
		5	10	.254
	Lowest	1	84	.003
		2	82	.003
		3	80	.003
		4	78	.003
		5	50	.003[g]
Si	Highest	1	79	47.60
		2	82	46.51
		3	72	45.99
		4	31	45.99
		5	67	45.88
	Lowest	1	4	19.66
		2	10	20.35
		3	12	21.66
		4	13	21.90
		5	1	23.58
Sr	Highest	1	10	.0960
		2	13	.0442
		3	12	.0258
		4	4	.0250
		5	1	.0236
	Lowest	1	2	.0092
		2	62	.0100
		3	46	.0100
		4	6	.0100
		5	3	.0100

Extreme Values

			Case Number	Value
Ti	Highest	1	10	.428
		2	13	.387
		3	1	.331
		4	12	.220
		5	8	.209
	Lowest	1	46	.026
		2	34	.026
		3	28	.028
		4	80	.030
		5	57	.030
Zr	Highest	1	10	.0122
		2	41	.0118
		3	13	.0090
		4	12	.0088
		5	22	.0088
	Lowest	1	28	.0036
		2	74	.0042
		3	45	.0042
		4	95	.0044
		5	92	.0044[h]

a. Only a partial list of cases with the value 6.9 are shown in the table of lower extremes.

b. Only a partial list of cases with the value 78.0 are shown in the table of lower extremes.

c. Only a partial list of cases with the value .024 are shown in the table of lower extremes.

d. Only a partial list of cases with the value .010 are shown in the table of upper extremes.

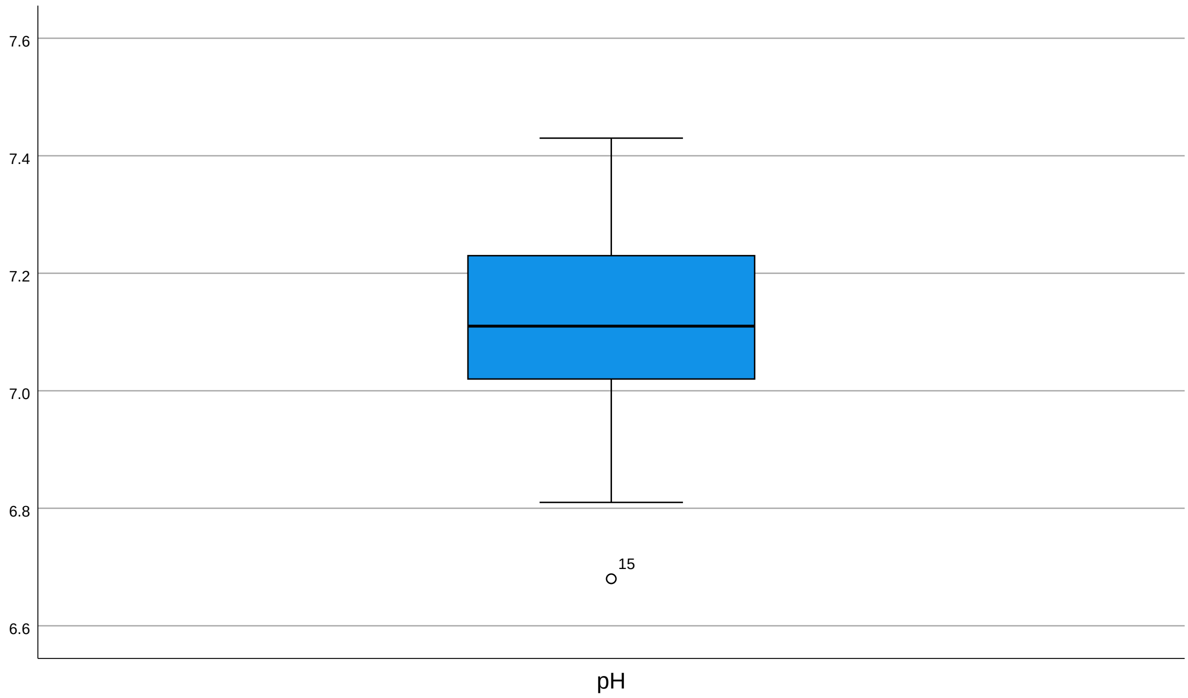
e. Only a partial list of cases with the value .002 are shown in the table of lower extremes.

f. Only a partial list of cases with the value .0034 are shown in the table of lower extremes.

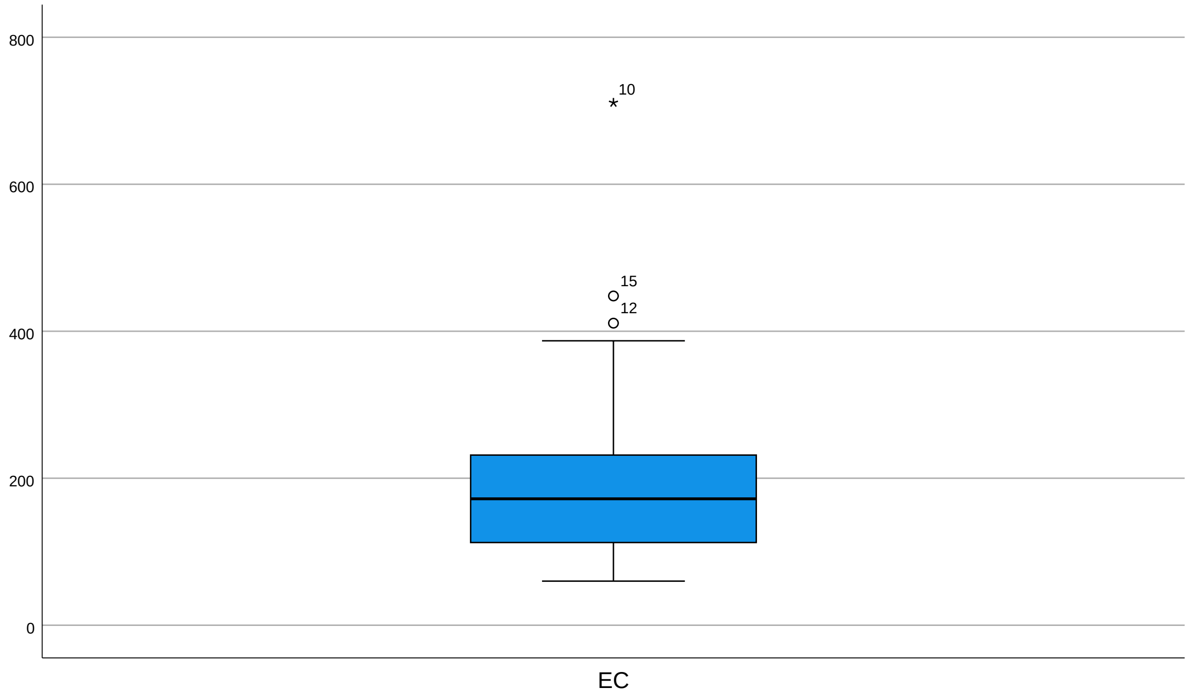
g. Only a partial list of cases with the value .003 are shown in the table of lower extremes.

h. Only a partial list of cases with the value .0044 are shown in the table of lower extremes.

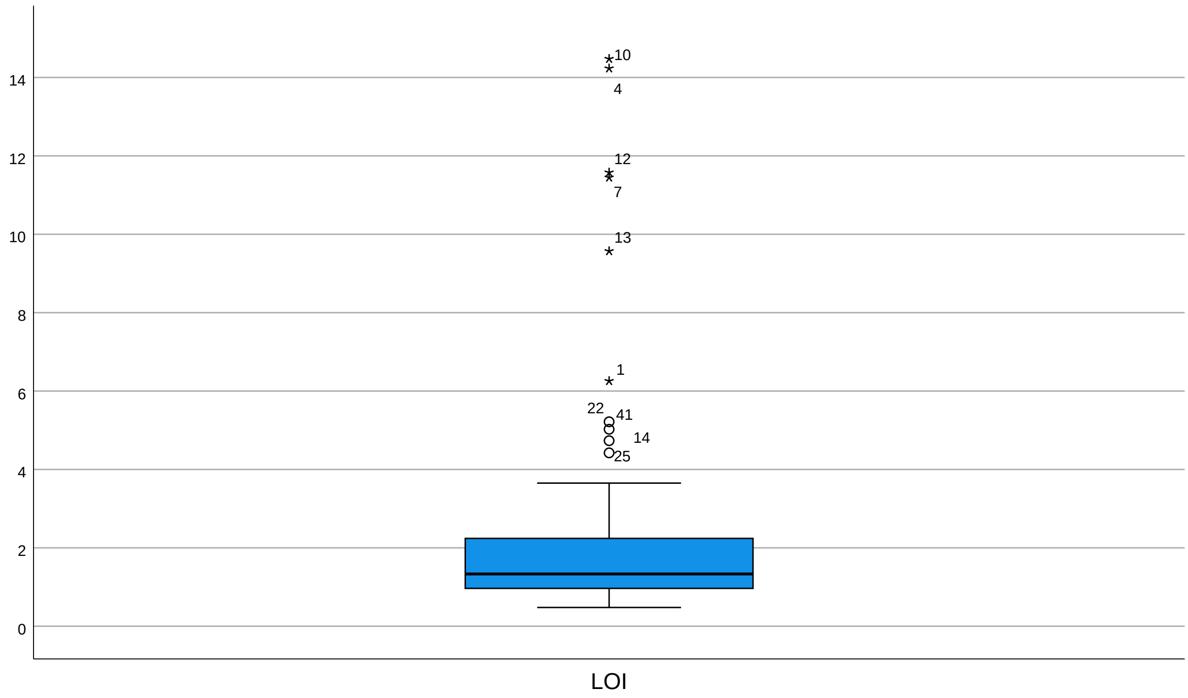
pH



EC

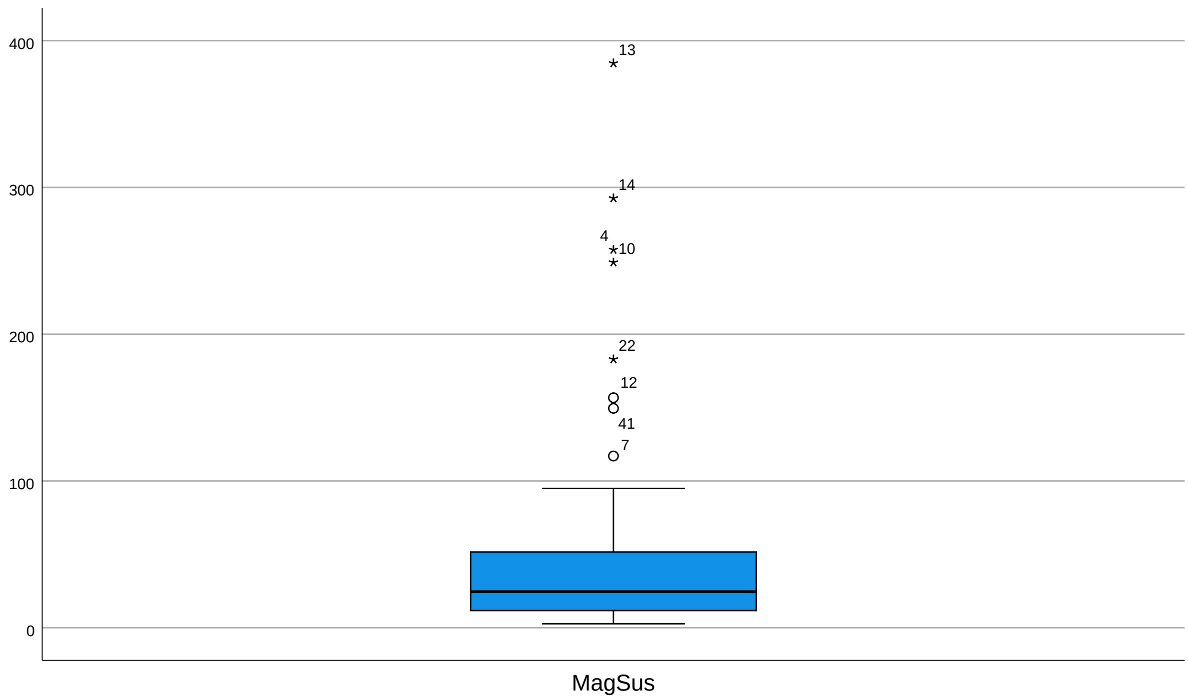


LOI



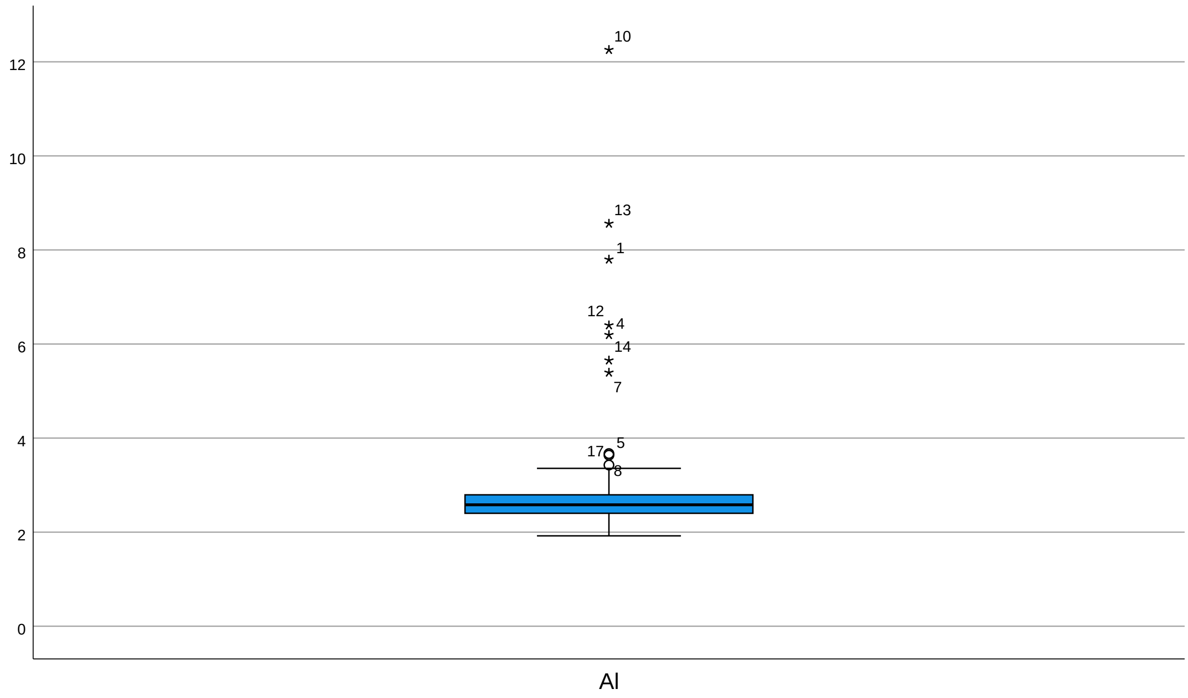
14
12
10
8
6
4
2
0
10
4
12
7
13
1
22
41
14
25
LOI

MagSus

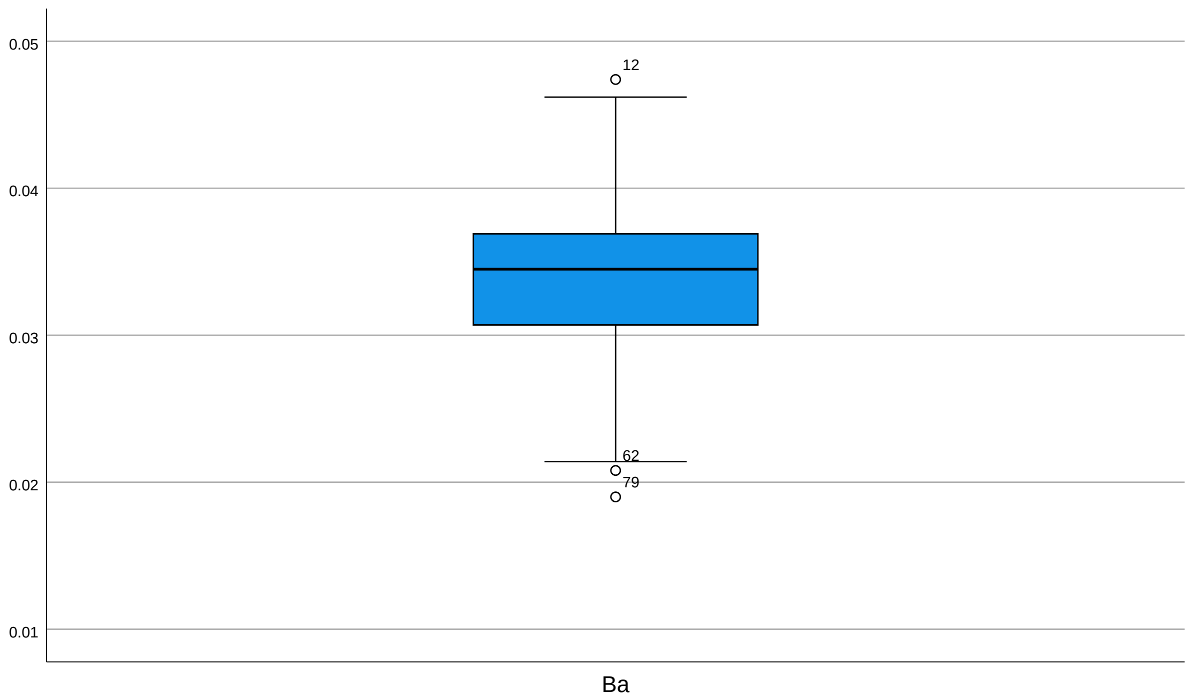


400
300
200
100
0
13
14
4
10
22
12
41
7
MagSus

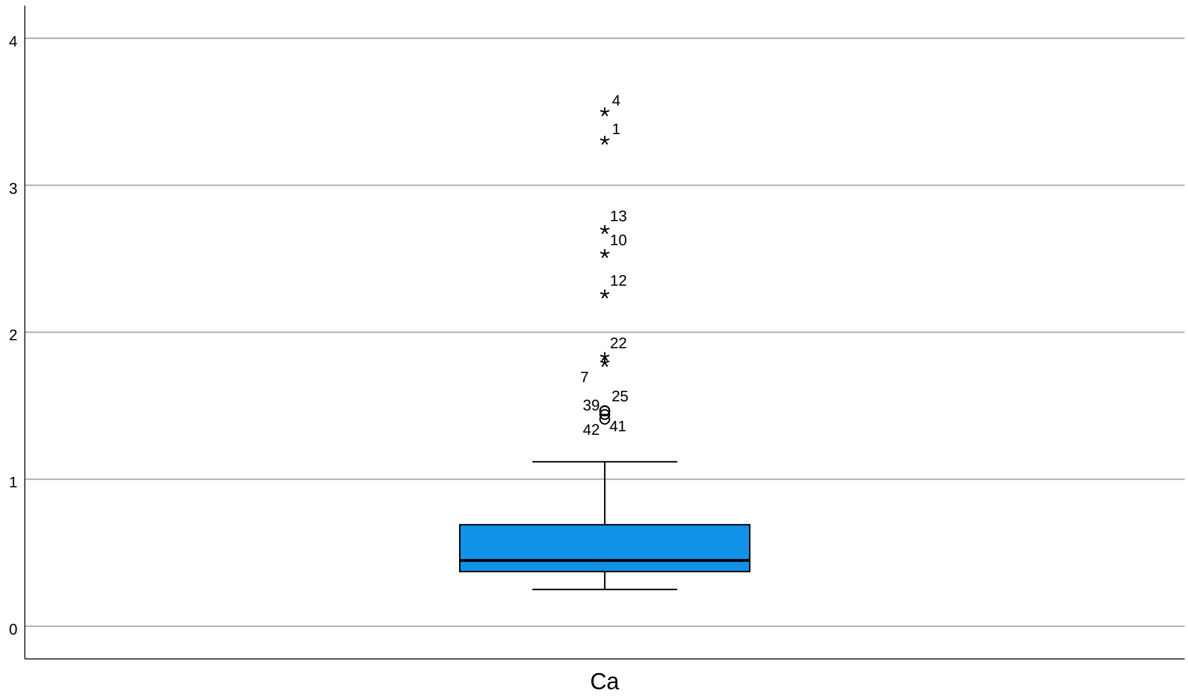
Al



Ba

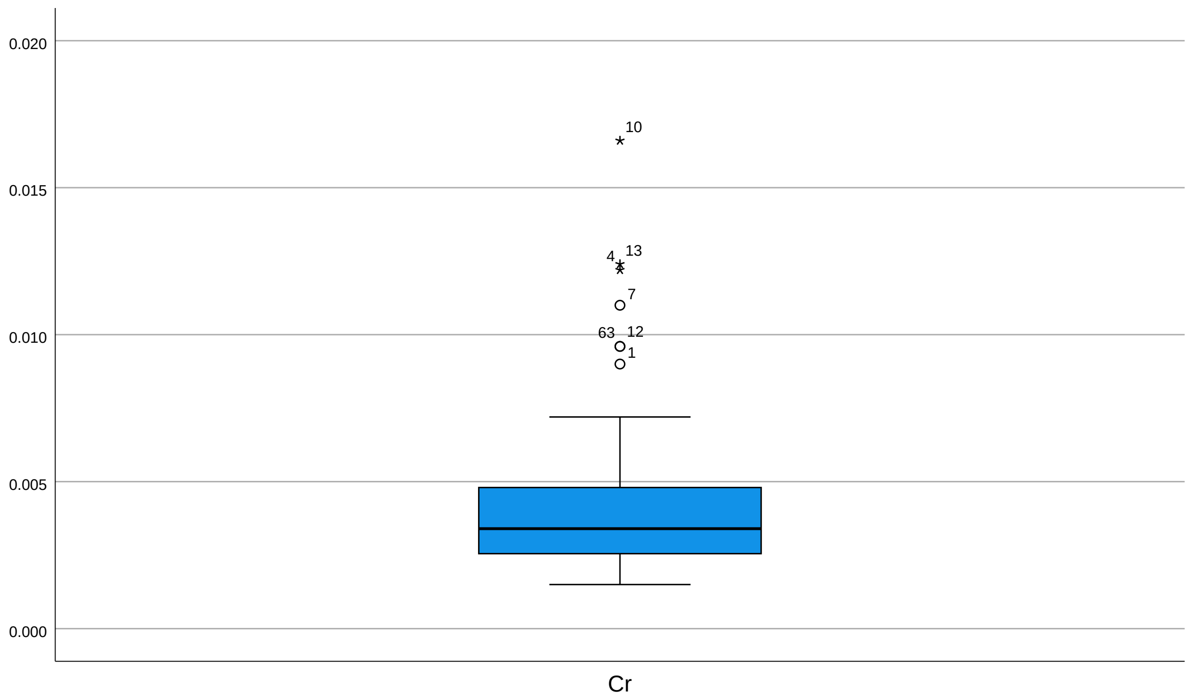


Ca



4
3
2
1
0
4
1
13
10
12
22
7
39
25
42
41
Ca

Cr



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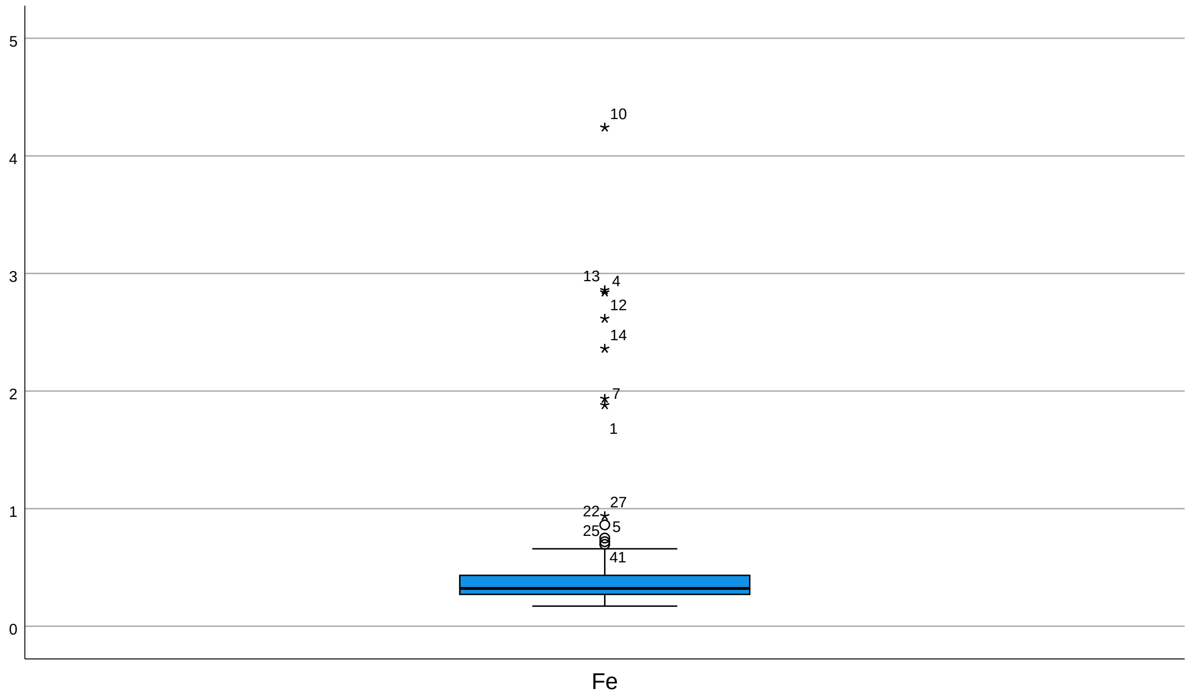
0.015
0.010
0.005
0.000
10
4
13
7
63
12
1
Cr

Fe


5
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3
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1
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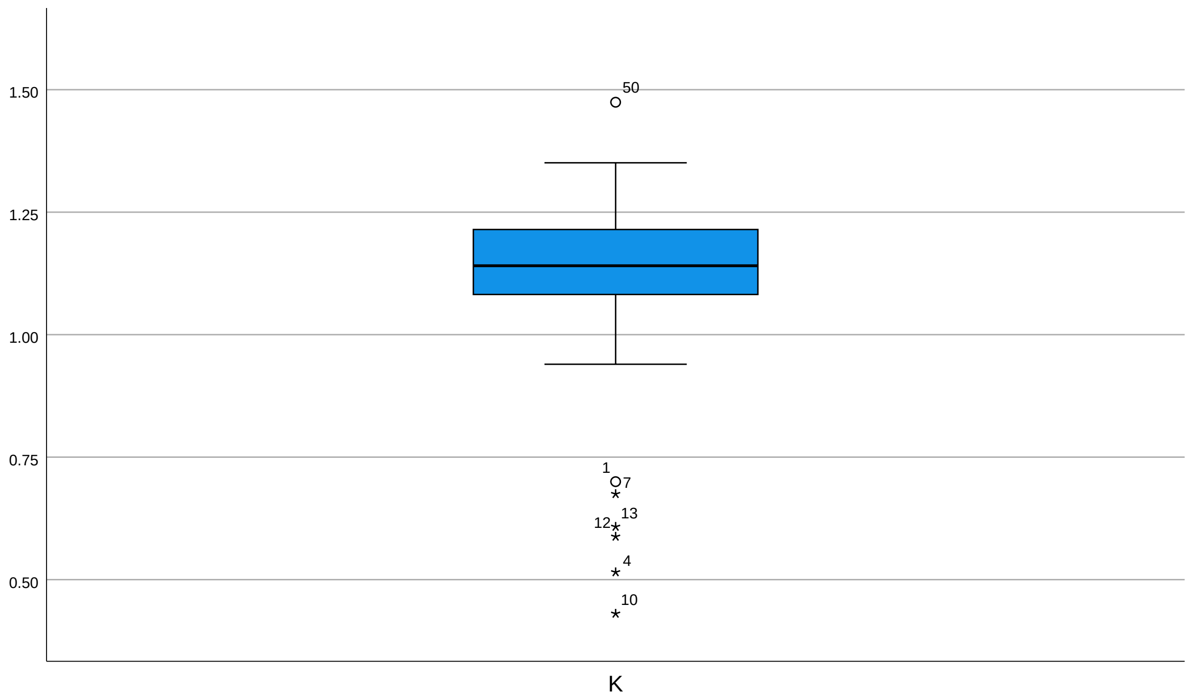
13
4
12
14
7
1
27
22
5
25
41
Fe

K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50
1
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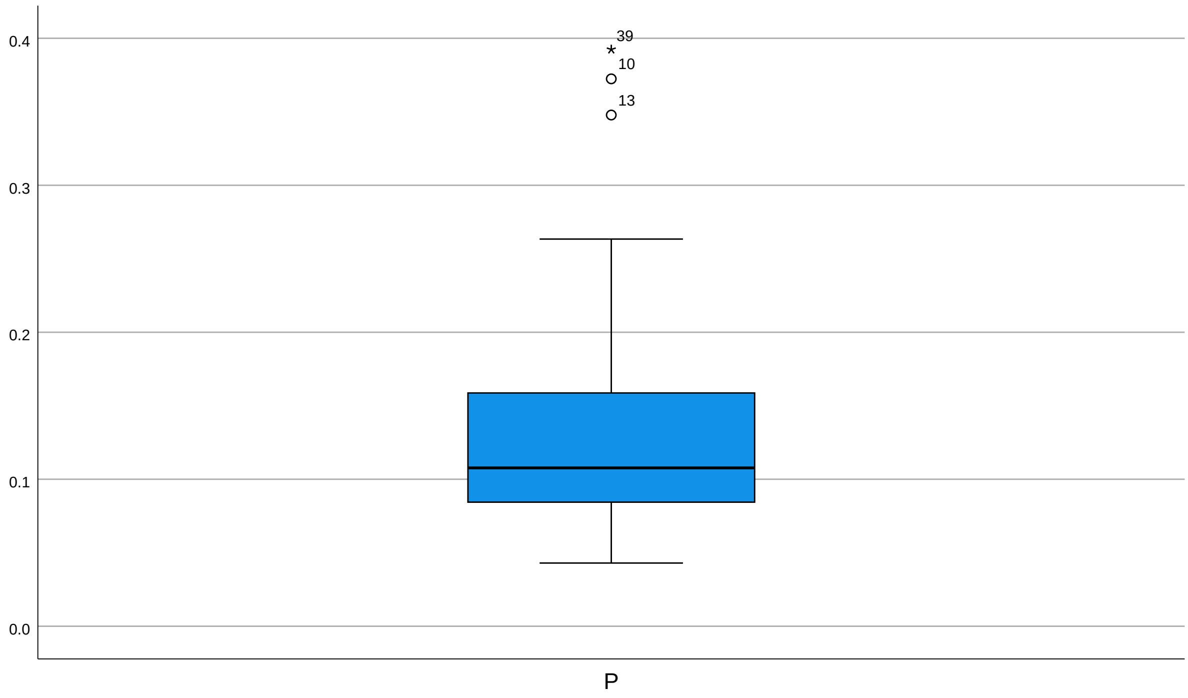
13
12
4
10
K

P



39
10
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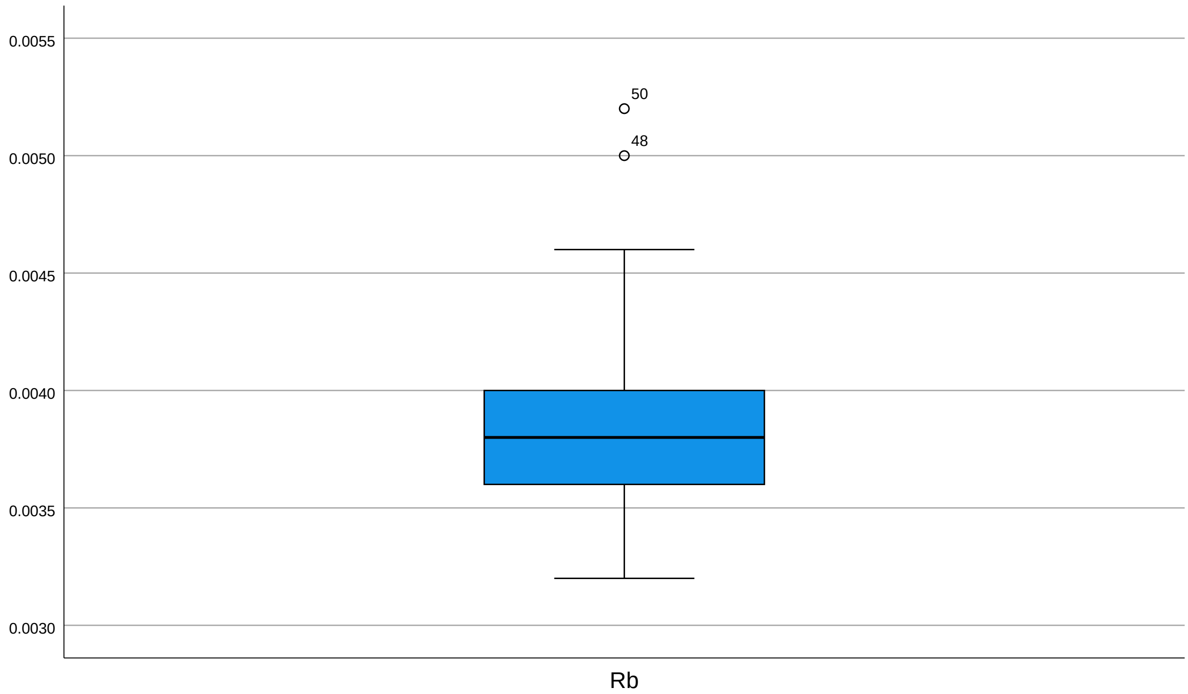
0.1
0.0
P

Rb



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48
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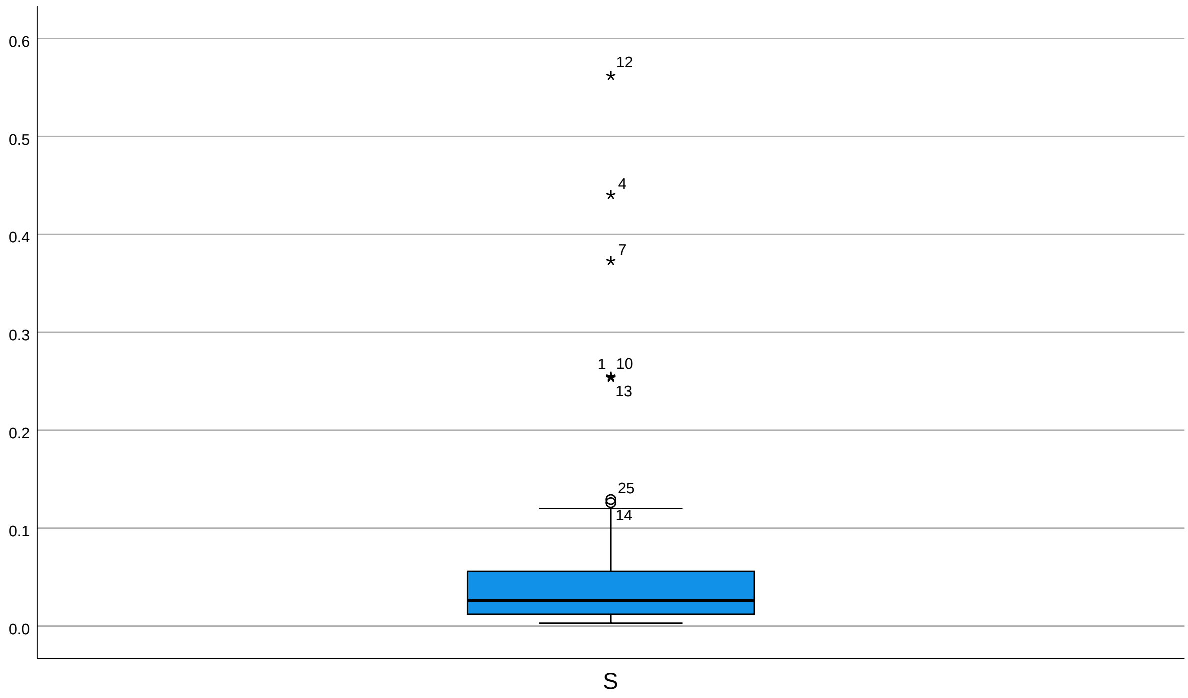
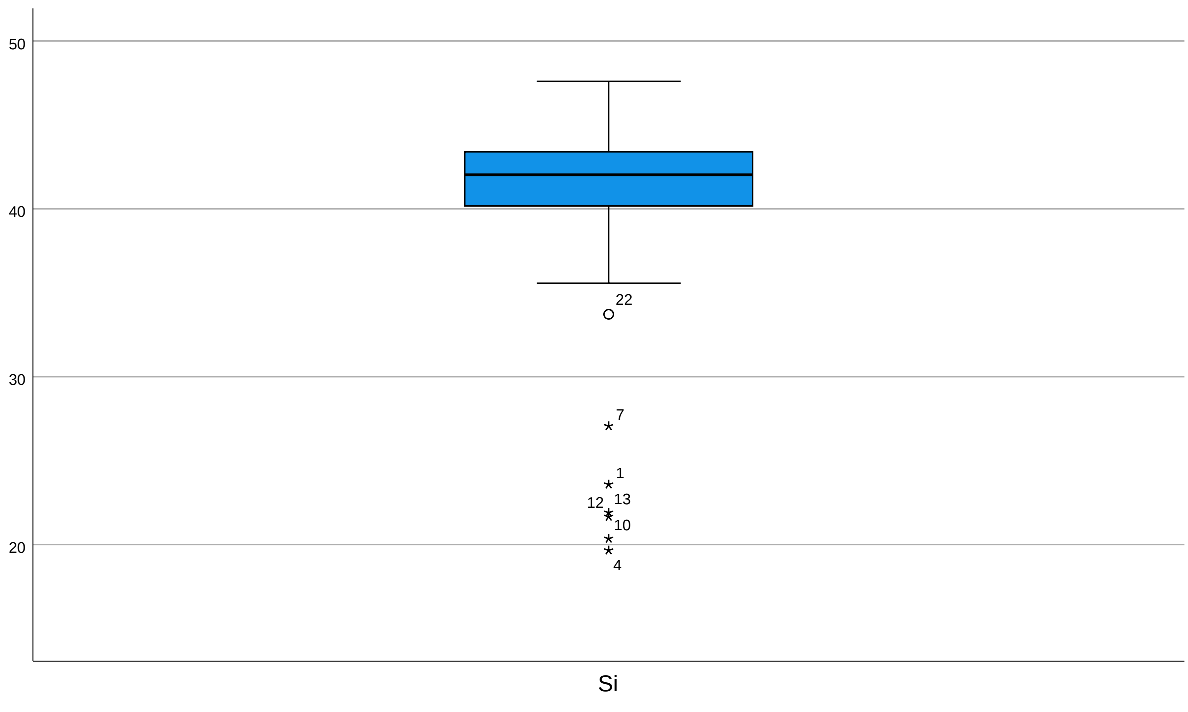
0.0050
0.0045
0.0040
0.0035
0.0030
Rb

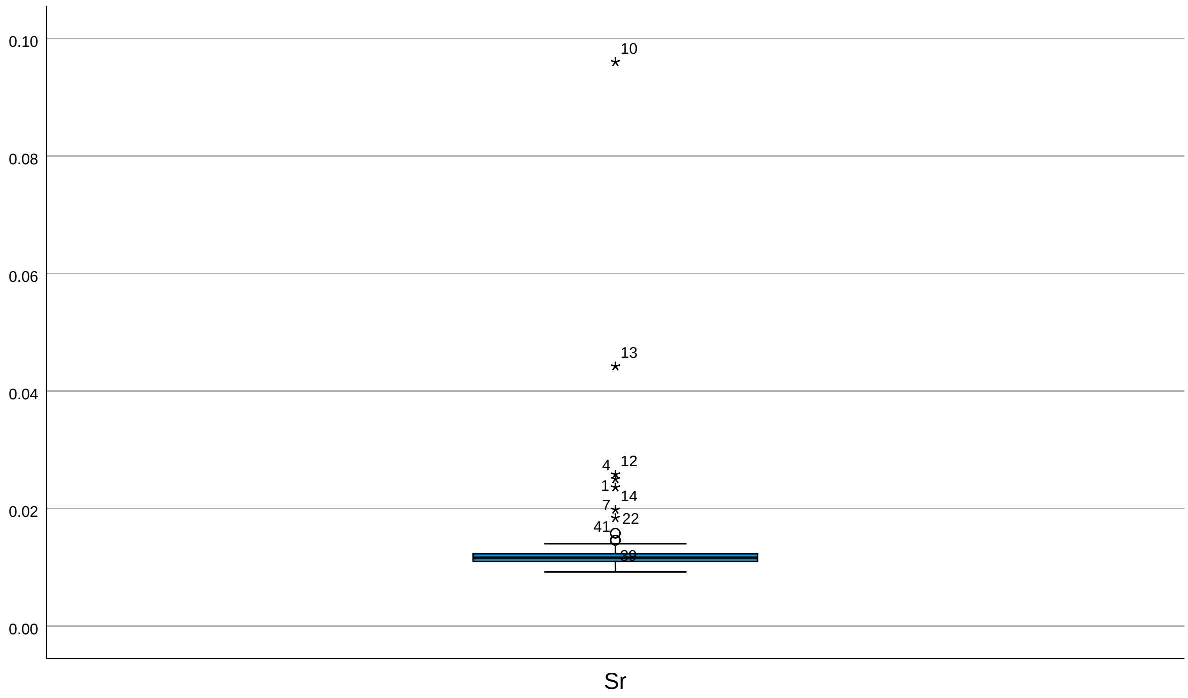
S



Si



Sr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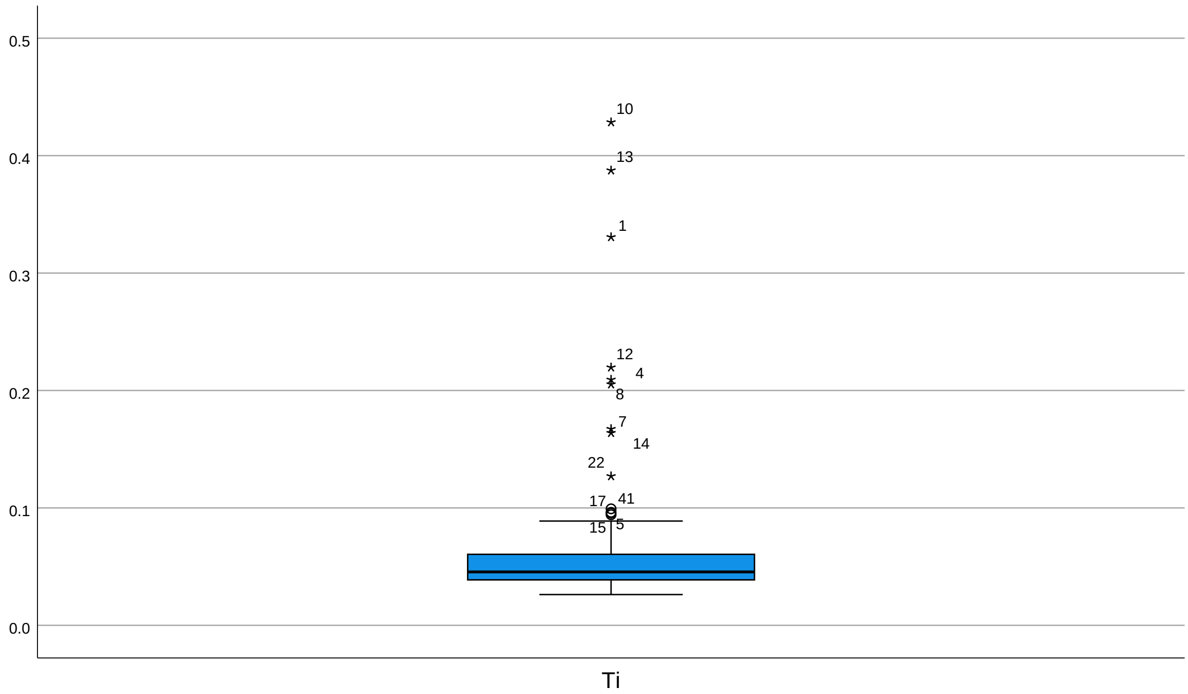
0.02
0.00
10
13
4
12
1
14
7
22
41
Sr

Ti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0.4
0.3
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0.1
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10
13
1
12
4
8
7
14
22
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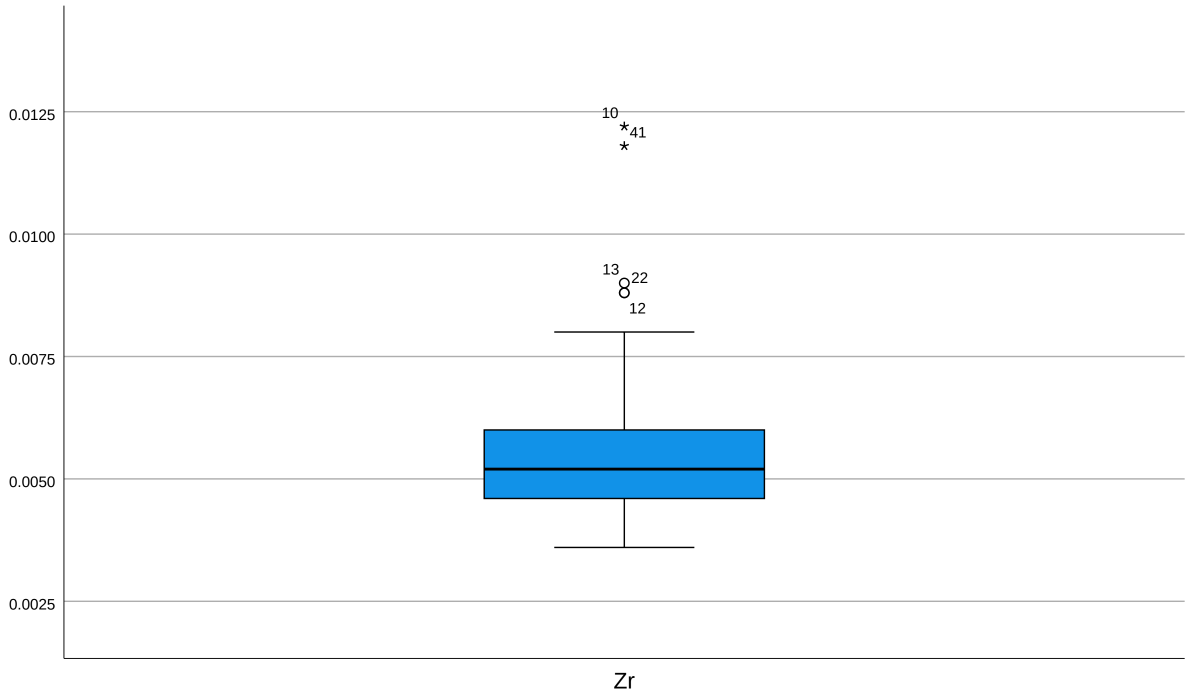
41
15
5
Ti

Zr



Factor Analysis

Notes

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	Active Dataset	DataSet6
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	N of Rows in Working Data File	96
Missing Value Handling	Definition of Missing	MISSING=EXCLUDE: User-defined missing values are treated as missing.
	Cases Used	LISTWISE: Statistics are based on cases with no missing values for any variable used.
Syntax		FACTOR /VARIABLES ZpH ZEC ZLOI ZMagSus ZAl ZBa ZCa ZCr ZFe ZK ZP ZRb ZS ZSi ZSr ZTi ZZr /MISSING LISTWISE /ANALYSIS ZpH ZEC ZLOI ZMagSus ZAl ZBa ZCa ZCr ZFe ZK ZP ZRb ZS ZSi ZSr ZTi ZZr /PRINT INITIAL CORRELATION SIG DET KMO EXTRACTION /PLOT EIGEN ROTATION /CRITERIA MINEIGEN(1) ITERATE(100) /EXTRACTION PC /ROTATION NOROTATE /METHOD=CORRELATIO...
Resources	Processor Time	00:00:00.19
	Elapsed Time	00:00:00.22
	Maximum Memory Required	35976 (35.133K) bytes

Correlation Matrix[a]

		Zscore(pH)	Zscore(EC)	Zscore(LOI)	Zscore (MagSus)
Correlation	Zscore(pH)	1.000	-.565	-.312	-.331
	Zscore(EC)	-.565	1.000	.743	.686
	Zscore(LOI)	-.312	.743	1.000	.823
	Zscore(MagSus)	-.331	.686	.823	1.000
	Zscore(Al)	-.256	.677	.843	.763
	Zscore(Ba)	-.258	.455	.506	.451
	Zscore(Ca)	-.336	.681	.896	.805
	Zscore(Cr)	-.237	.674	.850	.768
	Zscore(Fe)	-.278	.712	.924	.860
	Zscore(K)	.244	-.542	-.804	-.658
	Zscore(P)	-.345	.712	.706	.734
	Zscore(Rb)	.296	-.199	-.214	-.147
	Zscore(S)	-.294	.653	.927	.716
	Zscore(Si)	.299	-.699	-.937	-.815
	Zscore(Sr)	-.216	.638	.726	.658
	Zscore(Ti)	-.260	.676	.844	.802
	Zscore(Zr)	-.395	.702	.711	.670
Sig. (1-tailed)	Zscore(pH)		.000	.001	.000
	Zscore(EC)	.000		.000	.000
	Zscore(LOI)	.001	.000		.000
	Zscore(MagSus)	.000	.000	.000	
	Zscore(Al)	.006	.000	.000	.000
	Zscore(Ba)	.006	.000	.000	.000
	Zscore(Ca)	.000	.000	.000	.000
	Zscore(Cr)	.010	.000	.000	.000
	Zscore(Fe)	.003	.000	.000	.000
	Zscore(K)	.008	.000	.000	.000
	Zscore(P)	.000	.000	.000	.000
	Zscore(Rb)	.002	.026	.018	.076
	Zscore(S)	.002	.000	.000	.000
	Zscore(Si)	.002	.000	.000	.000
	Zscore(Sr)	.017	.000	.000	.000
	Zscore(Ti)	.005	.000	.000	.000
	Zscore(Zr)	.000	.000	.000	.000

Correlation Matrix[a]

		Zscore(Al)	Zscore(Ba)	Zscore(Ca)	Zscore(Cr)	Zscore(Fe)
Correlation	Zscore(pH)	-.256	-.258	-.336	-.237	-.278
	Zscore(EC)	.677	.455	.681	.674	.712
	Zscore(LOI)	.843	.506	.896	.850	.924
	Zscore(MagSus)	.763	.451	.805	.768	.860
	Zscore(Al)	1.000	.488	.791	.817	.948
	Zscore(Ba)	.488	1.000	.462	.477	.511
	Zscore(Ca)	.791	.462	1.000	.772	.841
	Zscore(Cr)	.817	.477	.772	1.000	.856
	Zscore(Fe)	.948	.511	.841	.856	1.000
	Zscore(K)	-.734	-.311	-.728	-.689	-.808
	Zscore(P)	.675	.466	.779	.638	.695
	Zscore(Rb)	-.213	-.110	-.132	-.161	-.231
	Zscore(S)	.742	.509	.852	.734	.835
	Zscore(Si)	-.830	-.466	-.929	-.811	-.894
	Zscore(Sr)	.894	.364	.620	.736	.843
	Zscore(Ti)	.951	.431	.846	.797	.914
	Zscore(Zr)	.647	.330	.694	.630	.672
Sig. (1-tailed)	Zscore(pH)	.006	.006	.000	.010	.003
	Zscore(EC)	.000	.000	.000	.000	.000
	Zscore(LOI)	.000	.000	.000	.000	.000
	Zscore(MagSus)	.000	.000	.000	.000	.000
	Zscore(Al)		.000	.000	.000	.000
	Zscore(Ba)	.000		.000	.000	.000
	Zscore(Ca)	.000	.000		.000	.000
	Zscore(Cr)	.000	.000	.000		.000
	Zscore(Fe)	.000	.000	.000	.000	
	Zscore(K)	.000	.001	.000	.000	.000
	Zscore(P)	.000	.000	.000	.000	.000
	Zscore(Rb)	.019	.143	.100	.059	.012
	Zscore(S)	.000	.000	.000	.000	.000
	Zscore(Si)	.000	.000	.000	.000	.000
	Zscore(Sr)	.000	.000	.000	.000	.000
	Zscore(Ti)	.000	.000	.000	.000	.000
	Zscore(Zr)	.000	.001	.000	.000	.000

Correlation Matrix[a]

		Zscore(K)	Zscore(P)	Zscore(Rb)	Zscore(S)	Zscore(Si)
Correlation	Zscore(pH)	.244	-.345	.296	-.294	.299
	Zscore(EC)	-.542	.712	-.199	.653	-.699
	Zscore(LOI)	-.804	.706	-.214	.927	-.937
	Zscore(MagSus)	-.658	.734	-.147	.716	-.815
	Zscore(Al)	-.734	.675	-.213	.742	-.830
	Zscore(Ba)	-.311	.466	-.110	.509	-.466
	Zscore(Ca)	-.728	.779	-.132	.852	-.929
	Zscore(Cr)	-.689	.638	-.161	.734	-.811
	Zscore(Fe)	-.808	.695	-.231	.835	-.894
	Zscore(K)	1.000	-.511	.503	-.756	.799
	Zscore(P)	-.511	1.000	-.153	.615	-.703
	Zscore(Rb)	.503	-.153	1.000	-.173	.152
	Zscore(S)	-.756	.615	-.173	1.000	-.904
	Zscore(Si)	.799	-.703	.152	-.904	1.000
	Zscore(Sr)	-.638	.601	-.181	.521	-.683
	Zscore(Ti)	-.745	.718	-.229	.752	-.868
	Zscore(Zr)	-.512	.616	-.184	.598	-.675
Sig. (1-tailed)	Zscore(pH)	.008	.000	.002	.002	.002
	Zscore(EC)	.000	.000	.026	.000	.000
	Zscore(LOI)	.000	.000	.018	.000	.000
	Zscore(MagSus)	.000	.000	.076	.000	.000
	Zscore(Al)	.000	.000	.019	.000	.000
	Zscore(Ba)	.001	.000	.143	.000	.000
	Zscore(Ca)	.000	.000	.100	.000	.000
	Zscore(Cr)	.000	.000	.059	.000	.000
	Zscore(Fe)	.000	.000	.012	.000	.000
	Zscore(K)		.000	.000	.000	.000
	Zscore(P)	.000		.069	.000	.000
	Zscore(Rb)	.000	.069		.046	.069
	Zscore(S)	.000	.000	.046		.000
	Zscore(Si)	.000	.000	.069	.000	
	Zscore(Sr)	.000	.000	.038	.000	.000
	Zscore(Ti)	.000	.000	.012	.000	.000
	Zscore(Zr)	.000	.000	.036	.000	.000

Correlation Matrix[a]

		Zscore(Sr)	Zscore(Ti)	Zscore(Zr)
Correlation	Zscore(pH)	-.216	-.260	-.395
	Zscore(EC)	.638	.676	.702
	Zscore(LOI)	.726	.844	.711
	Zscore(MagSus)	.658	.802	.670
	Zscore(Al)	.894	.951	.647
	Zscore(Ba)	.364	.431	.330
	Zscore(Ca)	.620	.846	.694
	Zscore(Cr)	.736	.797	.630
	Zscore(Fe)	.843	.914	.672
	Zscore(K)	-.638	-.745	-.512
	Zscore(P)	.601	.718	.616
	Zscore(Rb)	-.181	-.229	-.184
	Zscore(S)	.521	.752	.598
	Zscore(Si)	-.683	-.868	-.675
	Zscore(Sr)	1.000	.816	.621
	Zscore(Ti)	.816	1.000	.703
	Zscore(Zr)	.621	.703	1.000
Sig. (1-tailed)	Zscore(pH)	.017	.005	.000
	Zscore(EC)	.000	.000	.000
	Zscore(LOI)	.000	.000	.000
	Zscore(MagSus)	.000	.000	.000
	Zscore(Al)	.000	.000	.000
	Zscore(Ba)	.000	.000	.001
	Zscore(Ca)	.000	.000	.000
	Zscore(Cr)	.000	.000	.000
	Zscore(Fe)	.000	.000	.000
	Zscore(K)	.000	.000	.000
	Zscore(P)	.000	.000	.000
	Zscore(Rb)	.038	.012	.036
	Zscore(S)	.000	.000	.000
	Zscore(Si)	.000	.000	.000
	Zscore(Sr)		.000	.000
	Zscore(Ti)	.000		.000
	Zscore(Zr)	.000	.000	

a. Determinant = 7.41E-012

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.889
Bartlett's Test of Sphericity	Approx. Chi-Square	2268.066
	df	136
	Sig.	.000

Communalities

	Initial	Extraction
Zscore(pH)	1.000	.851
Zscore(EC)	1.000	.806
Zscore(LOI)	1.000	.922
Zscore(MagSus)	1.000	.779
Zscore(Al)	1.000	.880
Zscore(Ba)	1.000	.392
Zscore(Ca)	1.000	.850
Zscore(Cr)	1.000	.789
Zscore(Fe)	1.000	.950
Zscore(K)	1.000	.879
Zscore(P)	1.000	.690
Zscore(Rb)	1.000	.916
Zscore(S)	1.000	.760
Zscore(Si)	1.000	.897
Zscore(Sr)	1.000	.682
Zscore(Ti)	1.000	.886
Zscore(Zr)	1.000	.633

Extraction Method: Principal Component Analysis.

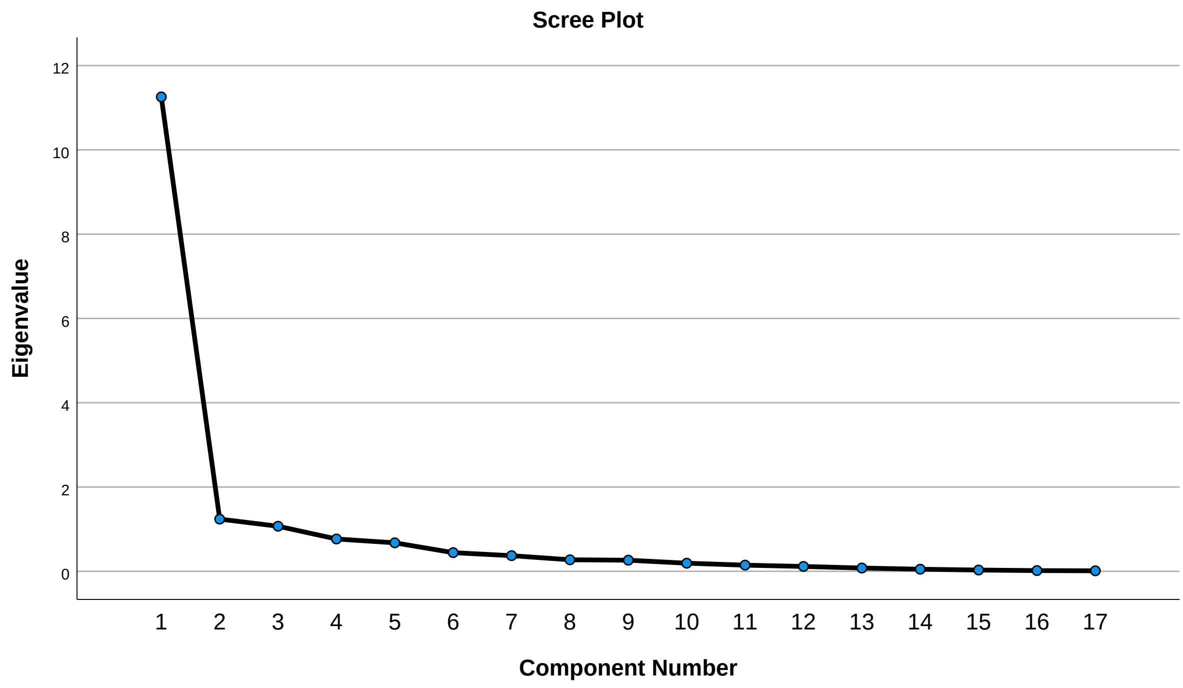
Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared ..	
	Total	% of Variance	Cumulative %	Total	% of Variance
1	11.256	66.210	66.210	11.256	66.210
2	1.239	7.286	73.496	1.239	7.286
3	1.070	6.292	79.788	1.070	6.292
4	.767	4.513	84.301		
5	.676	3.977	88.278		
6	.443	2.605	90.883		
7	.371	2.183	93.067		
8	.274	1.609	94.675		
9	.263	1.550	96.225		
10	.192	1.130	97.356		
11	.147	.862	98.218		
12	.115	.678	98.896		
13	.078	.458	99.353		
14	.050	.294	99.647		
15	.031	.180	99.827		
16	.017	.100	99.928		
17	.012	.072	100.000		

Total Variance Explained

Component	Extraction Sums ..
	Cumulative %
1	66.210
2	73.496
3	79.788
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	

Extraction Method: Principal Component Analysis.



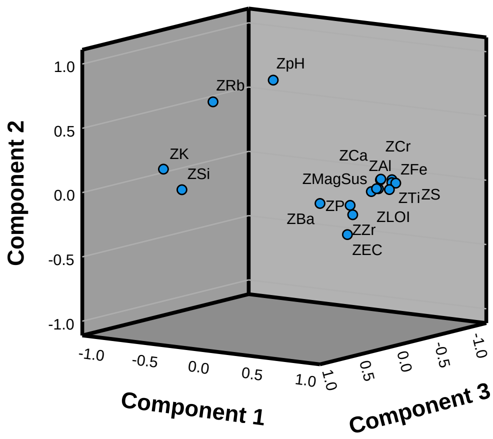
Component Matrix[a]

	Component		
	1	2	3
Zscore(pH)	-.391	.728	-.410
Zscore(EC)	.806	-.249	.308
Zscore(LOI)	.957	.067	-.037
Zscore(MagSus)	.876	.061	.089
Zscore(Al)	.921	.128	-.122
Zscore(Ba)	.547	-.033	.304
Zscore(Ca)	.915	.086	.074
Zscore(Cr)	.876	.140	-.038
Zscore(Fe)	.962	.106	-.115
Zscore(K)	-.811	.118	.456
Zscore(P)	.791	-.031	.251
Zscore(Rb)	-.261	.715	.580
Zscore(S)	.869	.068	-.016
Zscore(Si)	-.940	-.117	.025
Zscore(Sr)	.808	.114	-.130
Zscore(Ti)	.928	.107	-.111
Zscore(Zr)	.766	-.117	.180

Extraction Method: Principal Component Analysis.

a. 3 components extracted.

Component Plot



Burghead Lower Surface

Outliers

Factor Analysis

Outliers

Notes

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Missing Value Handling	Definition of Missing	User-defined missing values for dependent variables are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any dependent variable or factor used.
Syntax		EXAMINE VARIABLES=pH EC LOI Mag_Sus Al Ba Ca Cr Fe K P Rb S Si Sr Ti Zr /PLOT BOXPLOT /COMPARE GROUPS /STATISTICS DESCRIPTIVES EXTREME /CINTERVAL 95 /MISSING LISTWISE /NOTOTAL.
Resources	Processor Time	00:00:04.64
	Elapsed Time	00:00:05.80

Extreme Values

			Case Number	Value
pH	Highest	1	79	7.4
		2	90	7.3
		3	112	7.3
		4	80	7.3
		5	99	7.3[a]
	Lowest	1	19	6.6
		2	18	6.8
		3	34	6.8
		4	11	6.8
		5	130	6.8[b]
EC	Highest	1	19	602
		2	54	461
		3	28	391
		4	11	368
		5	18	335
	Lowest	1	89	24
		2	79	29
		3	121	35
		4	131	37
		5	120	38[c]
LOI	Highest	1	22	8.3
		2	54	7.3
		3	12	6.9
		4	44	5.8
		5	61	5.7
	Lowest	1	89	.3
		2	79	.5
		3	81	.5
		4	97	.5
		5	90	.5
Mag_Sus	Highest	1	54	206.5
		2	44	171.3
		3	34	155.8
		4	45	154.4
		5	55	123.9
	Lowest	1	121	2.3
		2	79	2.3
		3	91	2.4

Extreme Values

			Case Number	Value
		4	124	2.6
		5	90	2.7
Al	Highest	1	46	4.18
		2	44	3.81
		3	21	3.65
		4	9	3.64
		5	15	3.64
	Lowest	1	77	2.01
		2	124	2.27
		3	118	2.35
		4	116	2.36
		5	74	2.37
Ba	Highest	1	53	.041
		2	34	.041
		3	58	.039
		4	84	.039
		5	17	.038
	Lowest	1	62	.018
		2	103	.020
		3	32	.021
		4	81	.021
		5	89	.022
Ca	Highest	1	61	4.12
		2	60	2.91
		3	54	2.81
		4	12	2.14
		5	22	2.09
	Lowest	1	80	.27
		2	89	.29
		3	118	.30
		4	77	.30
		5	115	.31
Cr	Highest	1	9	.014
		2	94	.010
		3	130	.009
		4	53	.009
		5	61	.009

Extreme Values

			Case Number	Value
	Lowest	1	103	.002
		2	89	.002
		3	79	.002
		4	30	.002
		5	75	.002
Fe	Highest	1	54	.7
		2	61	.7
		3	78	.6
		4	22	.6
		5	34	.6
	Lowest	1	95	.2
		2	102	.2
		3	77	.2
		4	123	.2
		5	105	.2
K	Highest	1	44	1.72
		2	127	1.58
		3	9	1.57
		4	93	1.55
		5	105	1.52
	Lowest	1	79	.93
		2	116	.98
		3	103	.98
		4	77	.99
		5	118	1.05
P	Highest	1	8	.42
		2	60	.40
		3	61	.35
		4	54	.31
		5	17	.30
	Lowest	1	118	.05
		2	115	.05
		3	124	.05
		4	77	.06
		5	30	.07
Rb	Highest	1	44	.0054
		2	126	.0050
		3	61	.0048

Extreme Values

			Case Number	Value
		4	67	.0048
		5	84	.0046[d]
	Lowest	1	112	.0032
		2	124	.0034
		3	116	.0034
		4	97	.0034
		5	89	.0034[e]
S	Highest	1	19	.225
		2	54	.169
		3	12	.164
		4	61	.141
		5	22	.140
	Lowest	1	131	.003
		2	124	.003
		3	122	.003
		4	121	.003
		5	120	.003[f]
Si	Highest	1	89	56.98
		2	30	54.85
		3	79	53.09
		4	97	51.60
		5	112	51.35
	Lowest	1	54	33.17
		2	61	34.21
		3	12	35.15
		4	22	37.57
		5	1	38.42
Sr	Highest	1	56	.0184
		2	54	.0176
		3	22	.0170
		4	12	.0160
		5	61	.0160
	Lowest	1	100	.0100
		2	29	.0100
		3	88	.0102
		4	79	.0102
		5	80	.0104

Extreme Values

			Case Number	Value
Ti	Highest	1	22	.130
		2	54	.122
		3	44	.101
		4	55	.101
		5	60	.100
	Lowest	1	94	.031
		2	74	.031
		3	97	.032
		4	129	.032
		5	105	.033[g]
Zr	Highest	1	54	.0098
		2	111	.0098
		3	128	.0096
		4	12	.0094
		5	89	.0090
	Lowest	1	97	.0040
		2	81	.0040
		3	78	.0040
		4	129	.0042
		5	83	.0042[h]

a. Only a partial list of cases with the value 7.3 are shown in the table of upper extremes.

b. Only a partial list of cases with the value 6.8 are shown in the table of lower extremes.

c. Only a partial list of cases with the value 38 are shown in the table of lower extremes.

d. Only a partial list of cases with the value .0046 are shown in the table of upper extremes.

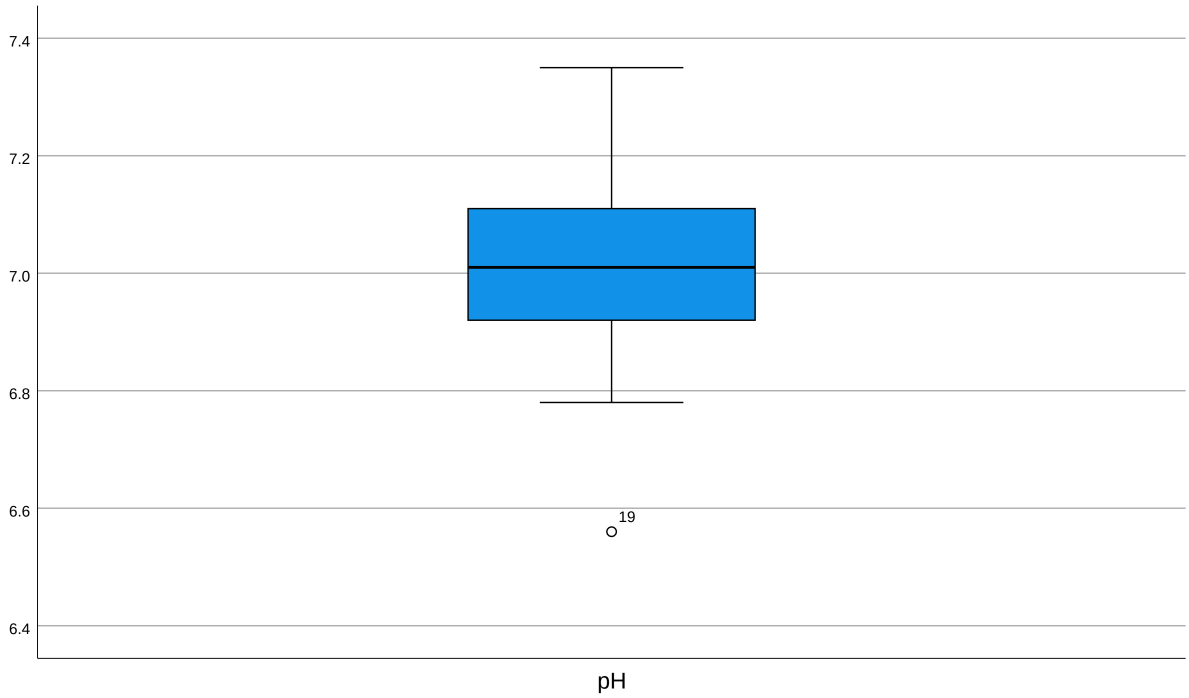
e. Only a partial list of cases with the value .0034 are shown in the table of lower extremes.

f. Only a partial list of cases with the value .003 are shown in the table of lower extremes.

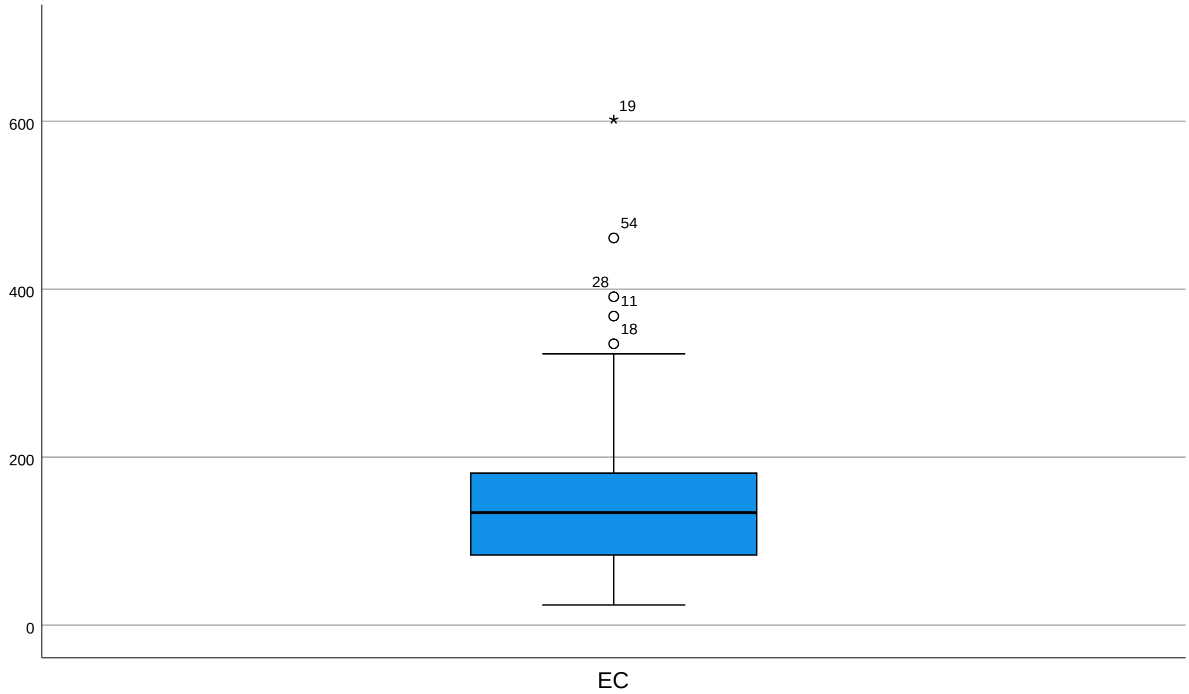
g. Only a partial list of cases with the value .033 are shown in the table of lower extremes.

h. Only a partial list of cases with the value .0042 are shown in the table of lower extremes.

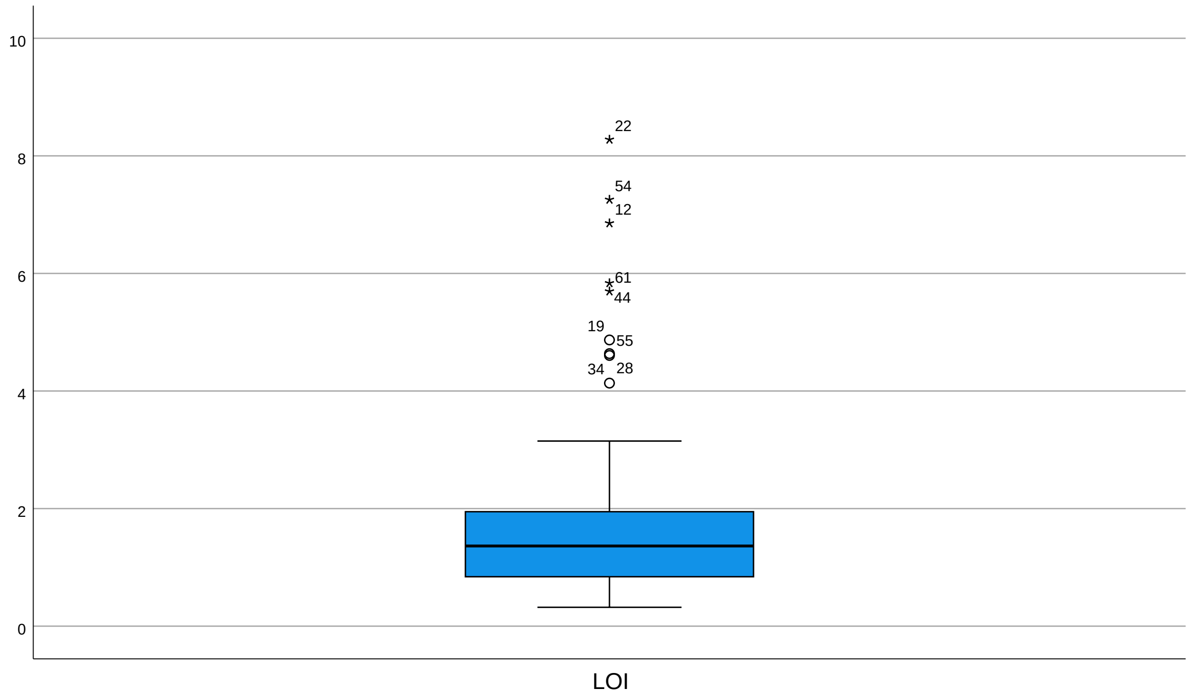
pH



EC

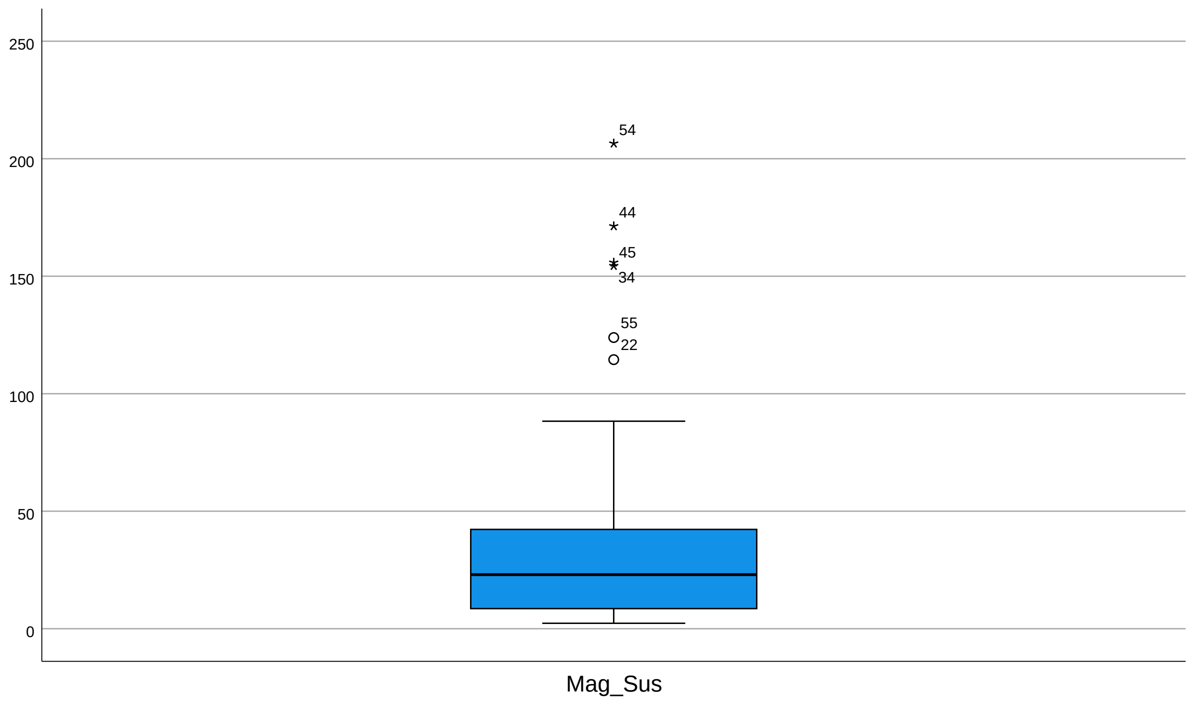


LOI



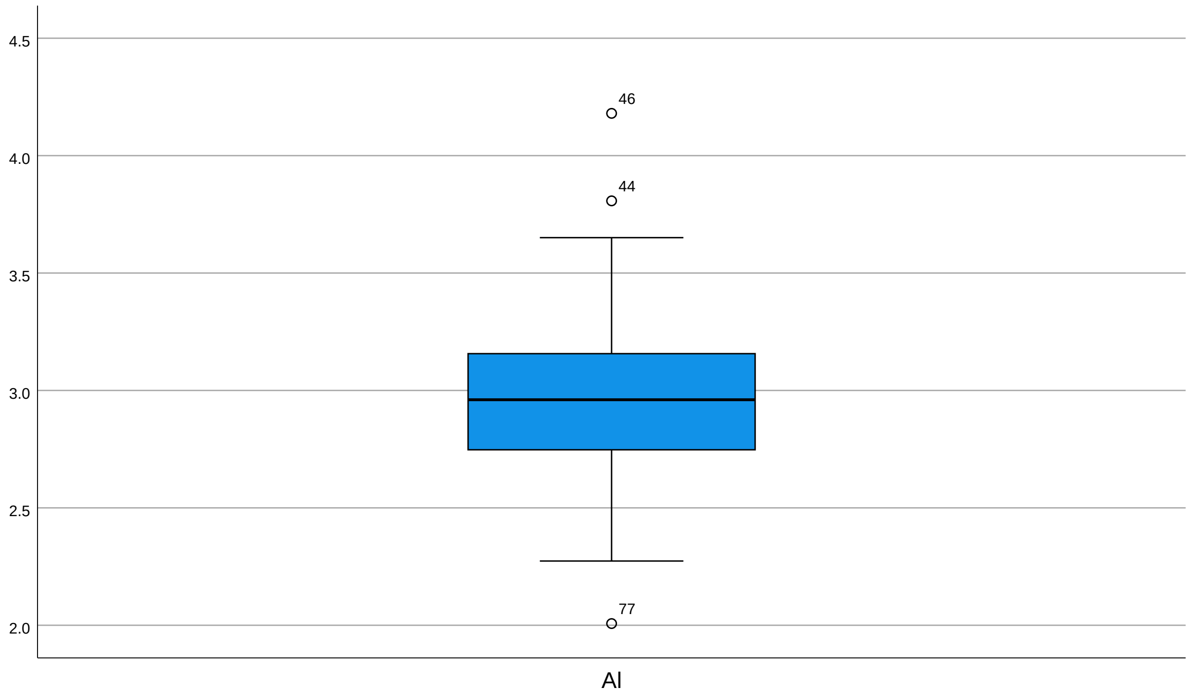
10
8
6
4
2
0
22
54
12
61
44
19
55
34
28
LOI

Mag_Sus



250
200
150
100
50
0
54
44
45
34
55
22
Mag_Sus

Al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3.5
3.0
2.5
2.0
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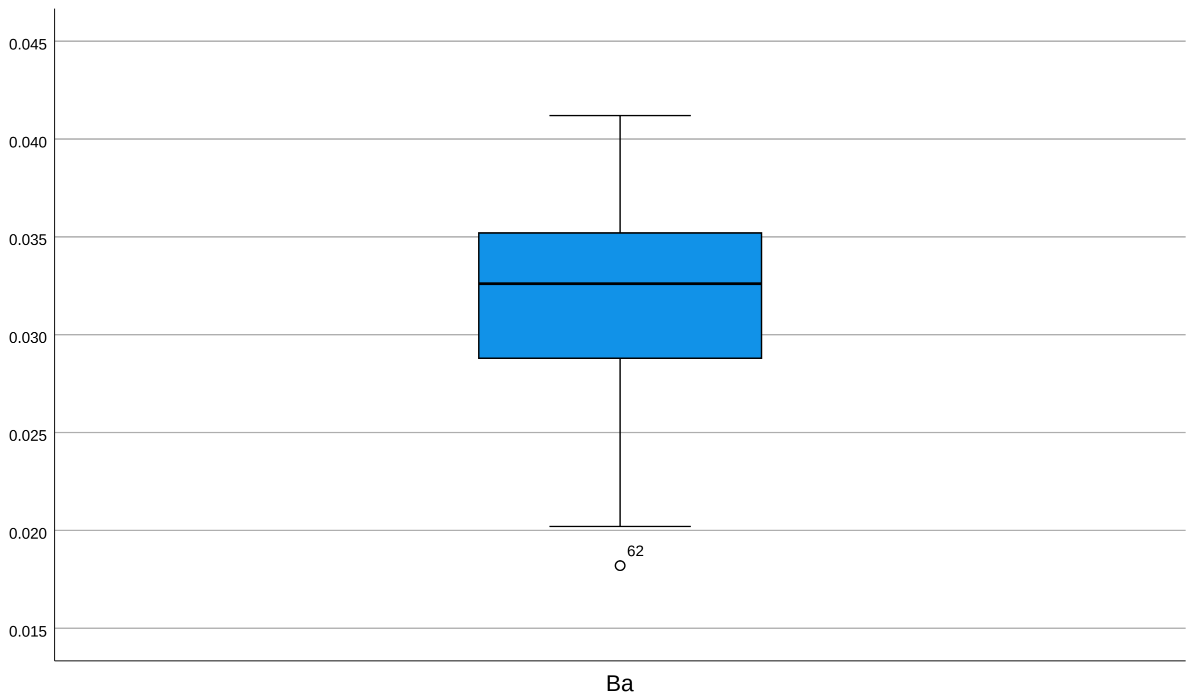
44
77
Al

Ba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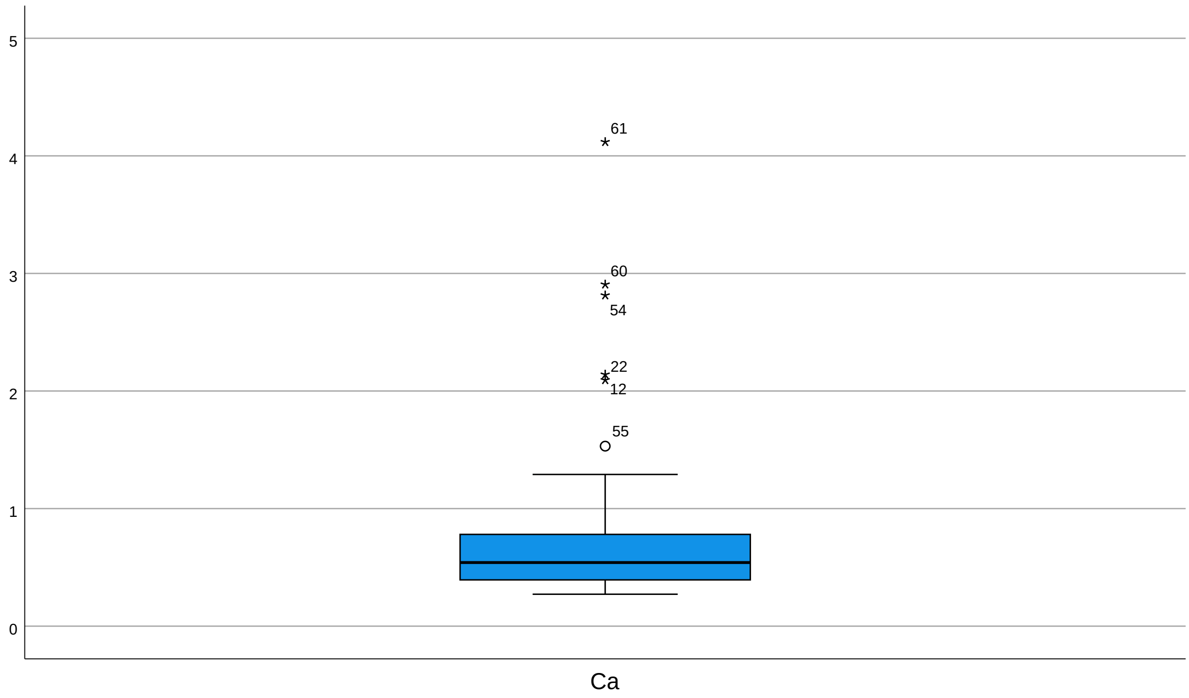
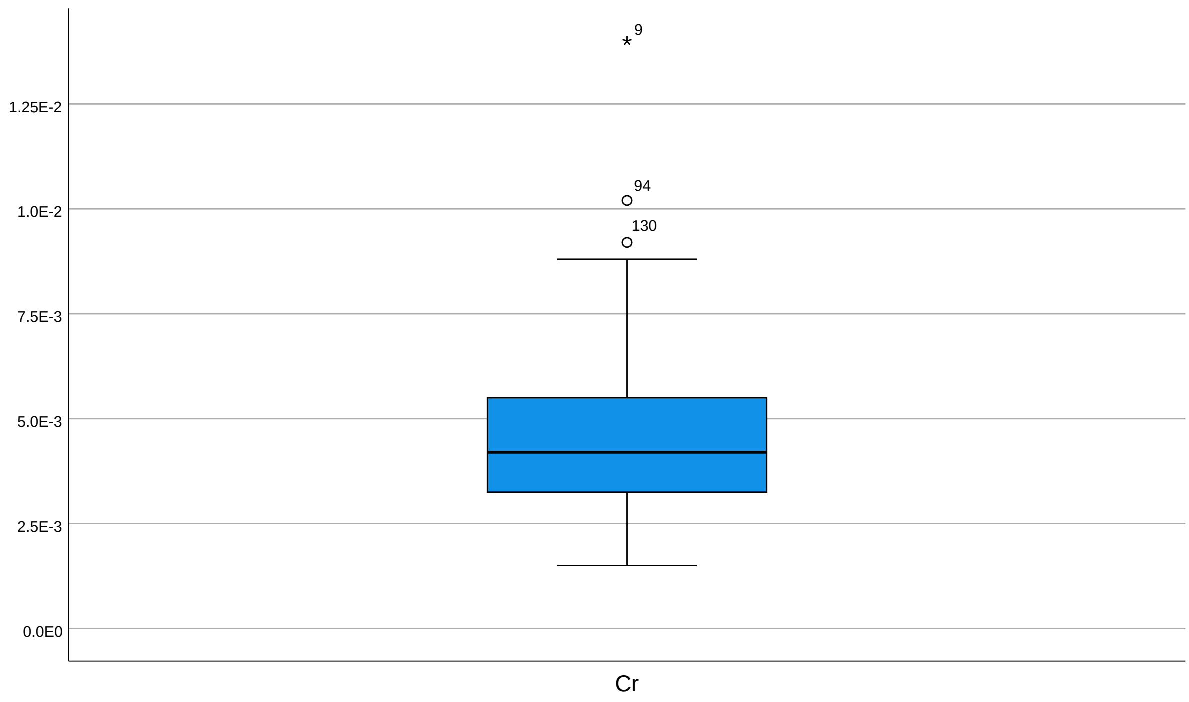
0.040
0.035
0.030
0.025
0.020
0.015
62
Ba

Ca



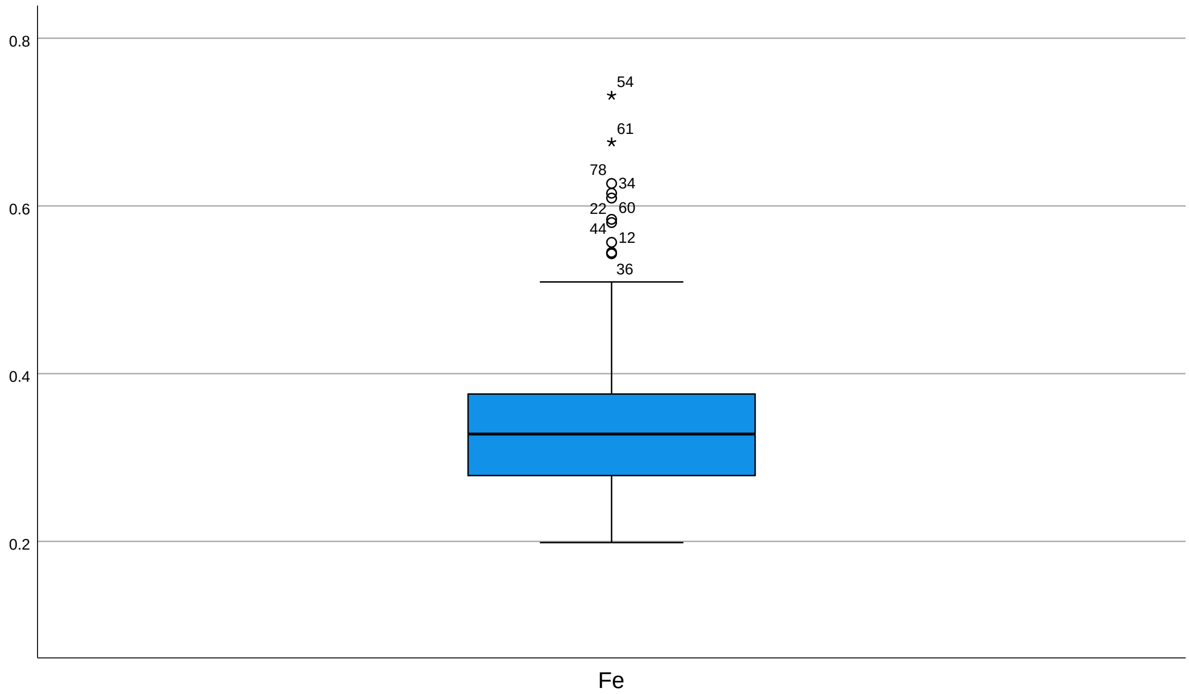
5
4
3
2
1
0
61
60
54
22
12
55
Ca

Cr

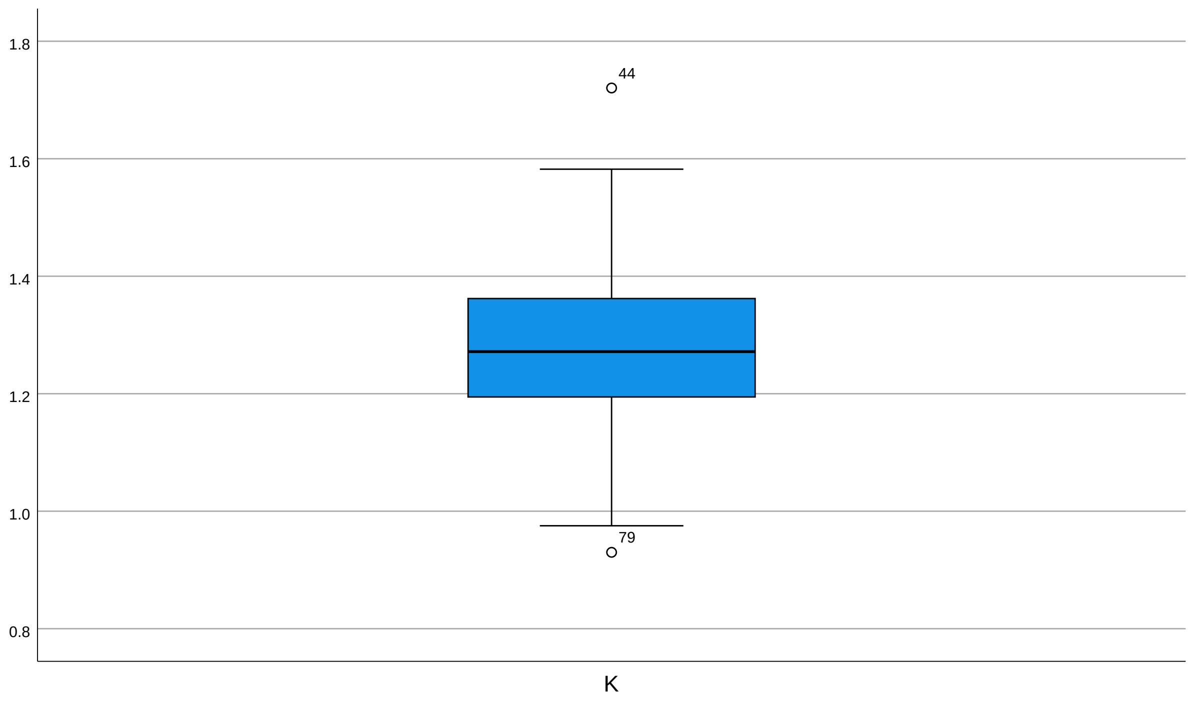


1.25E-2
1.0E-2
7.5E-3
5.0E-3
2.5E-3
0.0E0
9
94
130
Cr

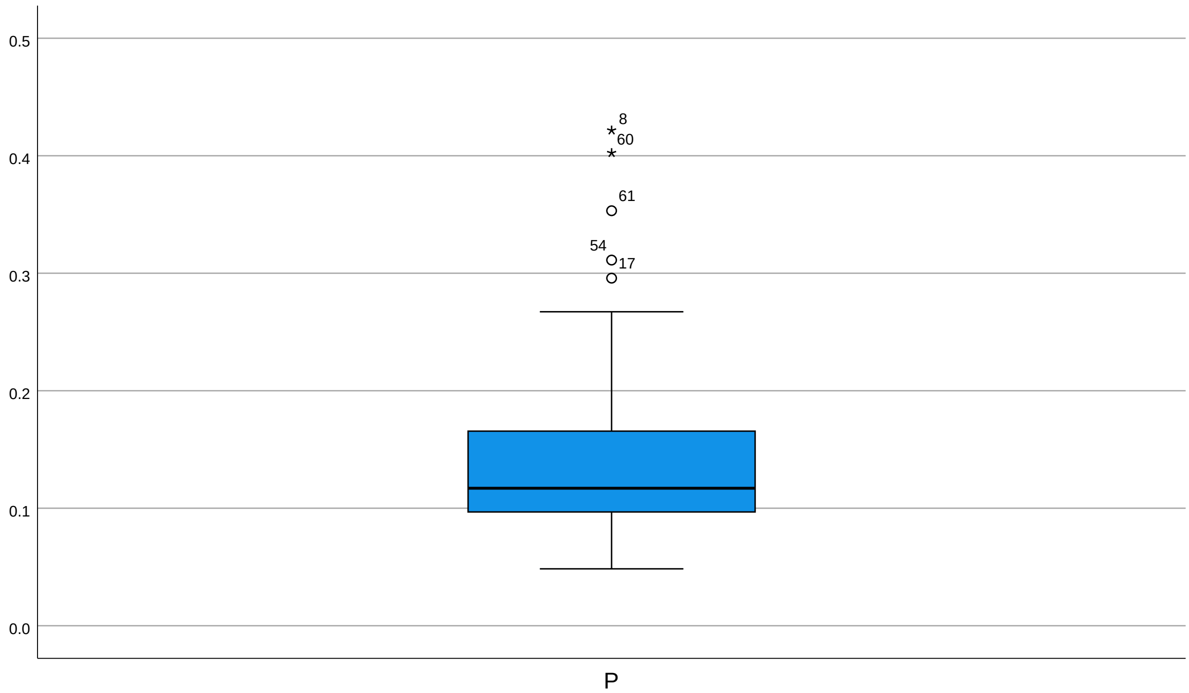
Fe



K



P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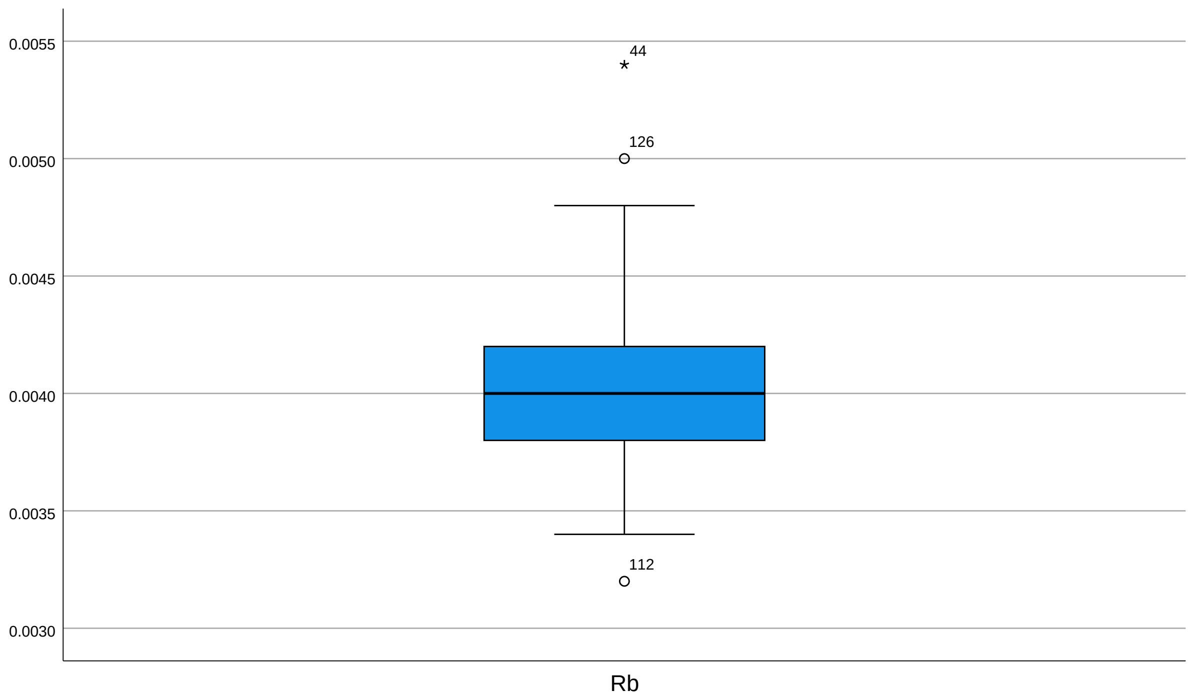
0.2
0.1
0.0
8
60
61
54
17
P

Rb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0.0045
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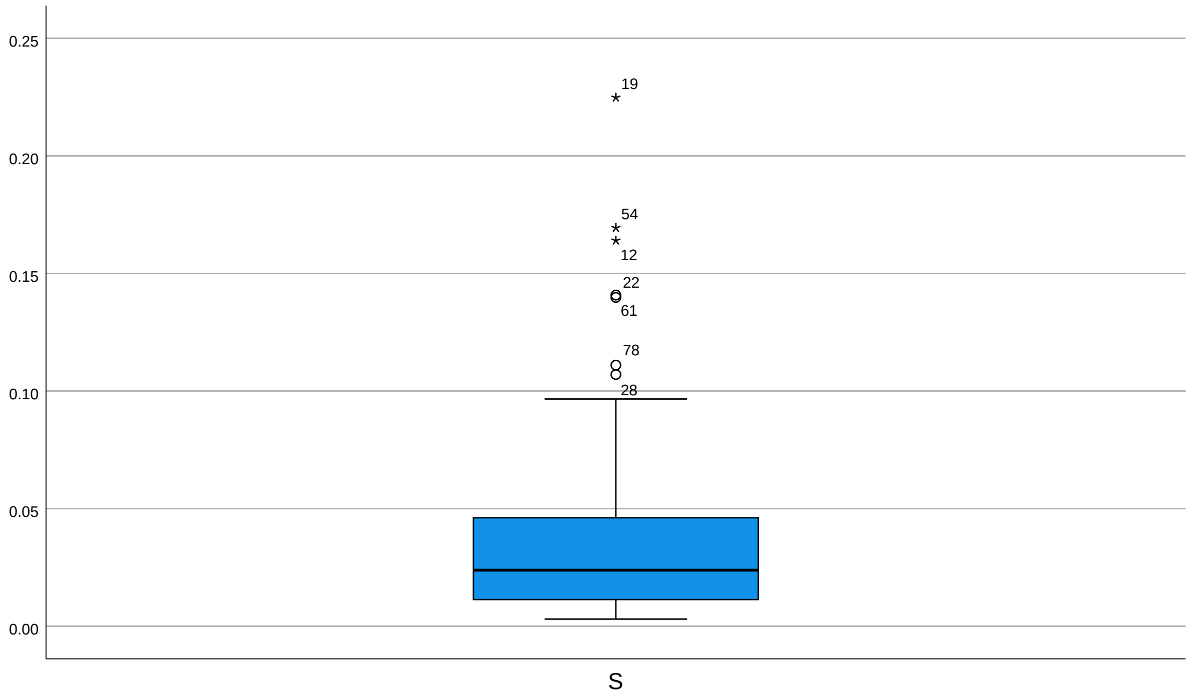
0.0035
0.0030
44
126
112
Rb

S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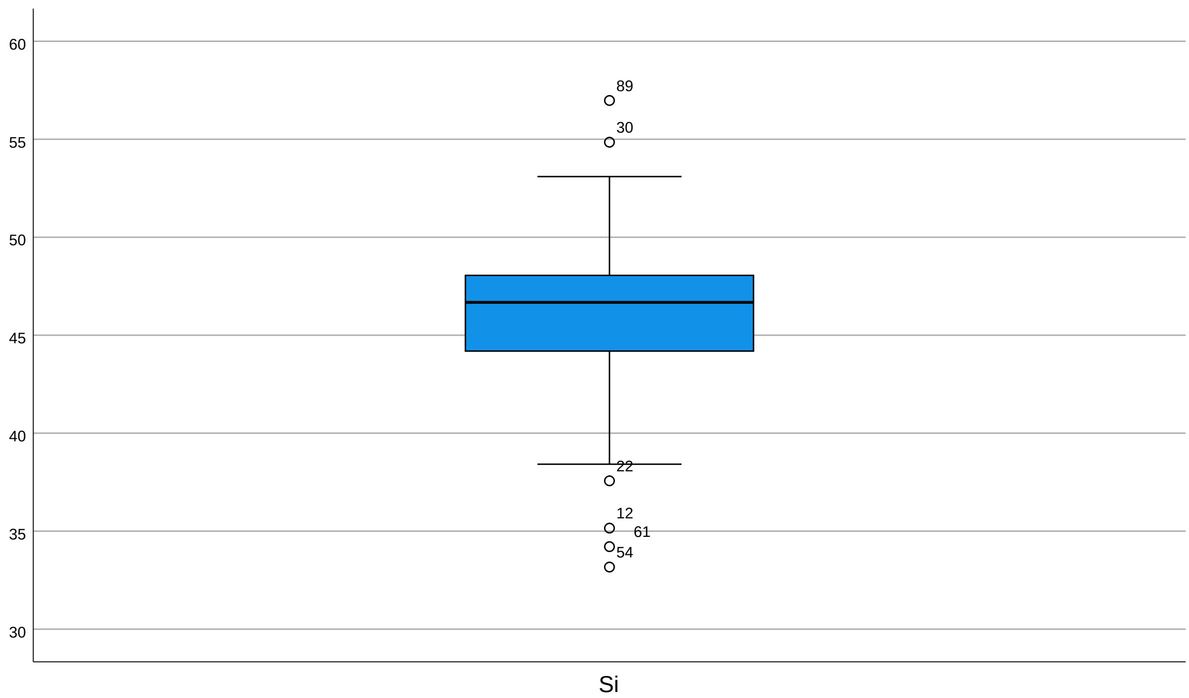
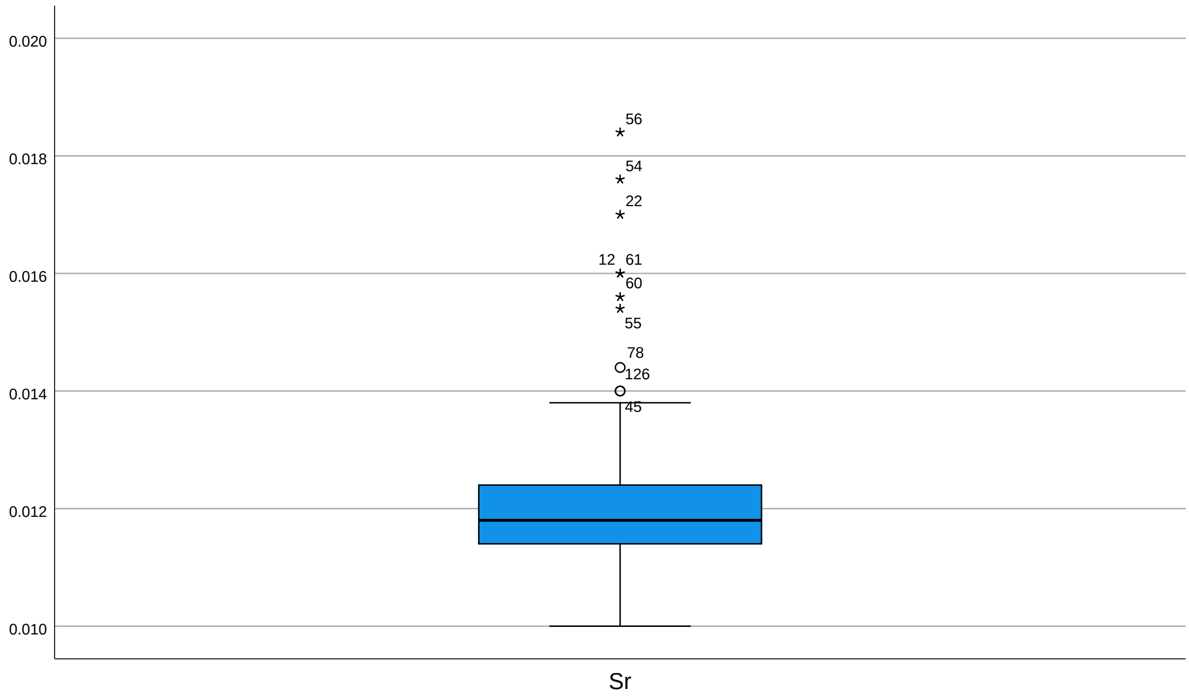
0.15
0.10
0.05
0.00
19
54
12
22
61
78
28
S

Si


60
55
50
45
40
35
30
89
30
22
12
61
54
Si

Sr


0.020
0.018
0.016
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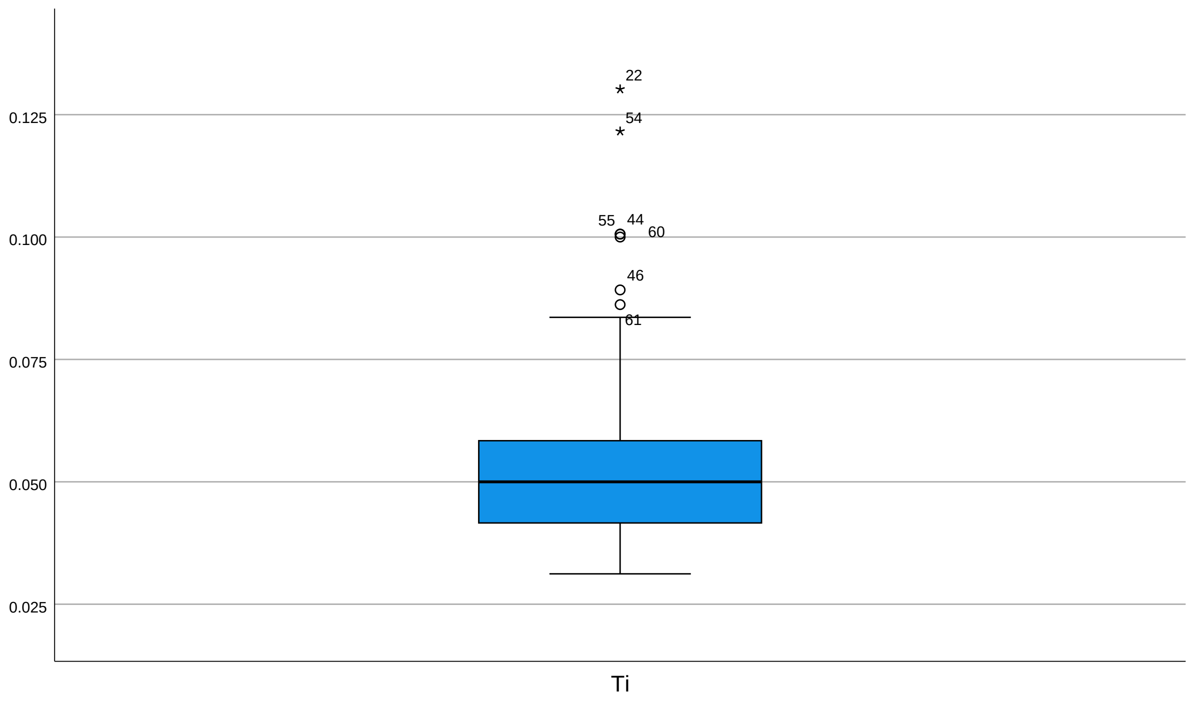
0.012
0.010
56
54
22
12
61
60
55
78
126
45
Sr

Ti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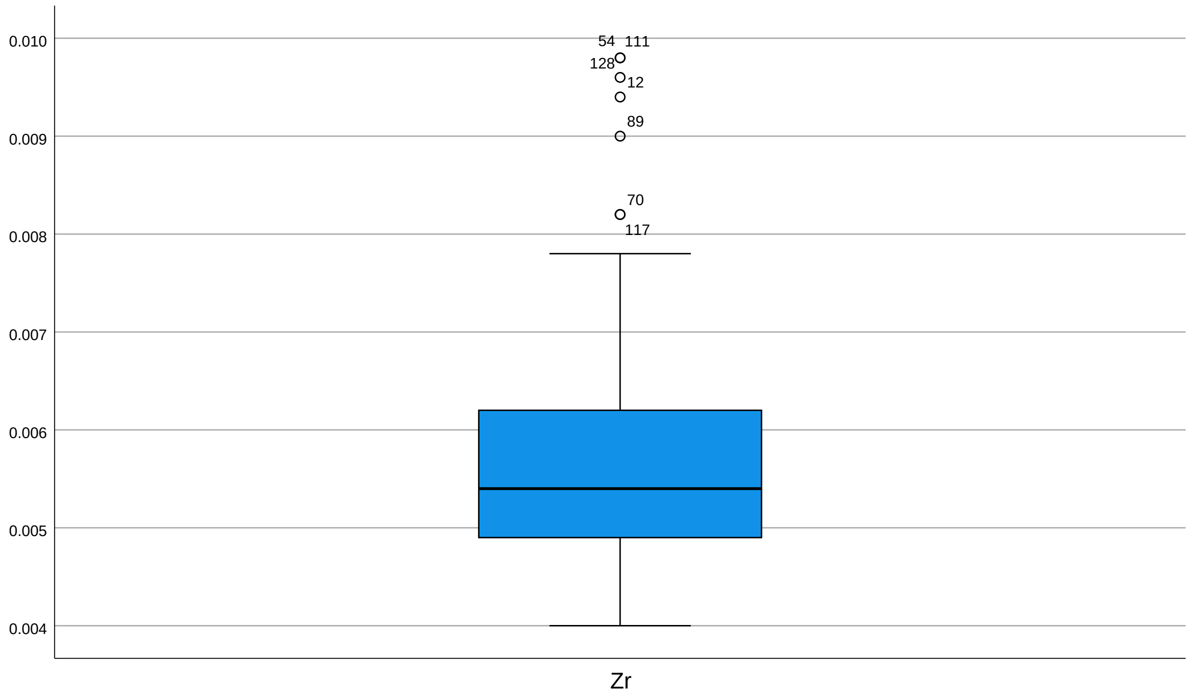
0.075
0.050
0.025
22
54
55
44
60
46
61
Ti

Zr



Factor Analysis

Notes

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Missing Value Handling	Definition of Missing	MISSING=EXCLUDE: User-defined missing values are treated as missing.
	Cases Used	LISTWISE: Statistics are based on cases with no missing values for any variable used.
Syntax		FACTOR /VARIABLES ZpH ZEC ZLOI ZMag_Sus ZAl ZBa ZCa ZCr ZFe ZK ZP ZRb ZS ZSi ZSr ZTi ZZr /MISSING LISTWISE /ANALYSIS ZpH ZEC ZLOI ZMag_Sus ZAl ZBa ZCa ZCr ZFe ZK ZP ZRb ZS ZSi ZSr ZTi ZZr /PRINT INITIAL CORRELATION SIG DET KMO EXTRACTION /PLOT EIGEN ROTATION /CRITERIA MINEIGEN(1) ITERATE(100) /EXTRACTION PC /ROTATION NOROTATE /METHOD=CORRELATIO...
Resources	Processor Time	00:00:00.61
	Elapsed Time	00:00:00.78
	Maximum Memory Required	35976 (35.133K) bytes

Correlation Matrix[a]

		Zscore(pH)	Zscore(EC)	Zscore(LOI)	Zscore (Mag_Sus)
Correlation	Zscore(pH)	1.000	-.776	-.483	-.429
	Zscore(EC)	-.776	1.000	.670	.588
	Zscore(LOI)	-.483	.670	1.000	.823
	Zscore(Mag_Sus)	-.429	.588	.823	1.000
	Zscore(Al)	-.246	.271	.291	.294
	Zscore(Ba)	-.079	.057	.157	.112
	Zscore(Ca)	-.291	.402	.814	.617
	Zscore(Cr)	-.389	.357	.429	.308
	Zscore(Fe)	-.436	.620	.820	.753
	Zscore(K)	-.037	-.025	-.084	-.012
	Zscore(P)	-.381	.393	.671	.572
	Zscore(Rb)	-.149	.178	.313	.317
	Zscore(S)	-.500	.714	.867	.630
	Zscore(Si)	.341	-.468	-.716	-.590
	Zscore(Sr)	-.234	.315	.690	.611
	Zscore(Ti)	-.430	.560	.786	.725
	Zscore(Zr)	-.184	.263	.437	.328
Sig. (1-tailed)	Zscore(pH)		.000	.000	.000
	Zscore(EC)	.000		.000	.000
	Zscore(LOI)	.000	.000		.000
	Zscore(Mag_Sus)	.000	.000	.000	
	Zscore(Al)	.002	.001	.000	.000
	Zscore(Ba)	.184	.258	.037	.101
	Zscore(Ca)	.000	.000	.000	.000
	Zscore(Cr)	.000	.000	.000	.000
	Zscore(Fe)	.000	.000	.000	.000
	Zscore(K)	.336	.387	.169	.444
	Zscore(P)	.000	.000	.000	.000
	Zscore(Rb)	.044	.021	.000	.000
	Zscore(S)	.000	.000	.000	.000
	Zscore(Si)	.000	.000	.000	.000
	Zscore(Sr)	.004	.000	.000	.000
	Zscore(Ti)	.000	.000	.000	.000
	Zscore(Zr)	.018	.001	.000	.000

Correlation Matrix[a]

		Zscore(Al)	Zscore(Ba)	Zscore(Ca)	Zscore(Cr)
Correlation	Zscore(pH)	-.246	-.079	-.291	-.389
	Zscore(EC)	.271	.057	.402	.357
	Zscore(LOI)	.291	.157	.814	.429
	Zscore(Mag_Sus)	.294	.112	.617	.308
	Zscore(Al)	1.000	.326	.320	.273
	Zscore(Ba)	.326	1.000	.158	.155
	Zscore(Ca)	.320	.158	1.000	.442
	Zscore(Cr)	.273	.155	.442	1.000
	Zscore(Fe)	.343	.145	.767	.422
	Zscore(K)	.616	.319	-.092	.125
	Zscore(P)	.457	.229	.784	.335
	Zscore(Rb)	.315	.167	.326	.180
	Zscore(S)	.368	.120	.772	.390
	Zscore(Si)	.089	-.088	-.672	-.363
	Zscore(Sr)	.334	.217	.734	.399
	Zscore(Ti)	.475	.163	.721	.254
	Zscore(Zr)	.052	.005	.378	.121
Sig. (1-tailed)	Zscore(pH)	.002	.184	.000	.000
	Zscore(EC)	.001	.258	.000	.000
	Zscore(LOI)	.000	.037	.000	.000
	Zscore(Mag_Sus)	.000	.101	.000	.000
	Zscore(Al)		.000	.000	.001
	Zscore(Ba)	.000		.036	.039
	Zscore(Ca)	.000	.036		.000
	Zscore(Cr)	.001	.039	.000	
	Zscore(Fe)	.000	.049	.000	.000
	Zscore(K)	.000	.000	.149	.078
	Zscore(P)	.000	.004	.000	.000
	Zscore(Rb)	.000	.028	.000	.020
	Zscore(S)	.000	.086	.000	.000
	Zscore(Si)	.157	.159	.000	.000
	Zscore(Sr)	.000	.006	.000	.000
	Zscore(Ti)	.000	.031	.000	.002
	Zscore(Zr)	.277	.478	.000	.085

Correlation Matrix[a]

		Zscore(Fe)	Zscore(K)	Zscore(P)	Zscore(Rb)	Zscore(S)
Correlation	Zscore(pH)	-.436	-.037	-.381	-.149	-.500
	Zscore(EC)	.620	-.025	.393	.178	.714
	Zscore(LOI)	.820	-.084	.671	.313	.867
	Zscore(Mag_Sus)	.753	-.012	.572	.317	.630
	Zscore(Al)	.343	.616	.457	.315	.368
	Zscore(Ba)	.145	.319	.229	.167	.120
	Zscore(Ca)	.767	-.092	.784	.326	.772
	Zscore(Cr)	.422	.125	.335	.180	.390
	Zscore(Fe)	1.000	-.065	.650	.298	.789
	Zscore(K)	-.065	1.000	.015	.453	-.057
	Zscore(P)	.650	.015	1.000	.276	.655
	Zscore(Rb)	.298	.453	.276	1.000	.283
	Zscore(S)	.789	-.057	.655	.283	1.000
	Zscore(Si)	-.591	.291	-.526	-.208	-.628
	Zscore(Sr)	.636	.063	.597	.323	.621
	Zscore(Ti)	.767	.075	.667	.326	.707
	Zscore(Zr)	.373	-.075	.214	.107	.315
Sig. (1-tailed)	Zscore(pH)	.000	.336	.000	.044	.000
	Zscore(EC)	.000	.387	.000	.021	.000
	Zscore(LOI)	.000	.169	.000	.000	.000
	Zscore(Mag_Sus)	.000	.444	.000	.000	.000
	Zscore(Al)	.000	.000	.000	.000	.000
	Zscore(Ba)	.049	.000	.004	.028	.086
	Zscore(Ca)	.000	.149	.000	.000	.000
	Zscore(Cr)	.000	.078	.000	.020	.000
	Zscore(Fe)		.230	.000	.000	.000
	Zscore(K)	.230		.430	.000	.260
	Zscore(P)	.000	.430		.001	.000
	Zscore(Rb)	.000	.000	.001		.001
	Zscore(S)	.000	.260	.000	.001	
	Zscore(Si)	.000	.000	.000	.008	.000
	Zscore(Sr)	.000	.238	.000	.000	.000
	Zscore(Ti)	.000	.196	.000	.000	.000
	Zscore(Zr)	.000	.197	.007	.112	.000

Correlation Matrix[a]

		Zscore(Si)	Zscore(Sr)	Zscore(Ti)	Zscore(Zr)
Correlation	Zscore(pH)	.341	-.234	-.430	-.184
	Zscore(EC)	-.468	.315	.560	.263
	Zscore(LOI)	-.716	.690	.786	.437
	Zscore(Mag_Sus)	-.590	.611	.725	.328
	Zscore(Al)	.089	.334	.475	.052
	Zscore(Ba)	-.088	.217	.163	.005
	Zscore(Ca)	-.672	.734	.721	.378
	Zscore(Cr)	-.363	.399	.254	.121
	Zscore(Fe)	-.591	.636	.767	.373
	Zscore(K)	.291	.063	.075	-.075
	Zscore(P)	-.526	.597	.667	.214
	Zscore(Rb)	-.208	.323	.326	.107
	Zscore(S)	-.628	.621	.707	.315
	Zscore(Si)	1.000	-.588	-.464	-.198
	Zscore(Sr)	-.588	1.000	.591	.194
	Zscore(Ti)	-.464	.591	1.000	.430
	Zscore(Zr)	-.198	.194	.430	1.000
Sig. (1-tailed)	Zscore(pH)	.000	.004	.000	.018
	Zscore(EC)	.000	.000	.000	.001
	Zscore(LOI)	.000	.000	.000	.000
	Zscore(Mag_Sus)	.000	.000	.000	.000
	Zscore(Al)	.157	.000	.000	.277
	Zscore(Ba)	.159	.006	.031	.478
	Zscore(Ca)	.000	.000	.000	.000
	Zscore(Cr)	.000	.000	.002	.085
	Zscore(Fe)	.000	.000	.000	.000
	Zscore(K)	.000	.238	.196	.197
	Zscore(P)	.000	.000	.000	.007
	Zscore(Rb)	.008	.000	.000	.112
	Zscore(S)	.000	.000	.000	.000
	Zscore(Si)		.000	.000	.012
	Zscore(Sr)	.000		.000	.013
	Zscore(Ti)	.000	.000		.000
	Zscore(Zr)	.012	.013	.000	

a. Determinant = 5.636E-7

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.866
Bartlett's Test of Sphericity	Approx. Chi-Square	1777.029
	df	136
	Sig.	.000

Communalities

	Initial	Extraction
Zscore(pH)	1.000	.841
Zscore(EC)	1.000	.888
Zscore(LOI)	1.000	.909
Zscore(Mag_Sus)	1.000	.695
Zscore(Al)	1.000	.758
Zscore(Ba)	1.000	.407
Zscore(Ca)	1.000	.869
Zscore(Cr)	1.000	.535
Zscore(Fe)	1.000	.800
Zscore(K)	1.000	.838
Zscore(P)	1.000	.667
Zscore(Rb)	1.000	.425
Zscore(S)	1.000	.797
Zscore(Si)	1.000	.778
Zscore(Sr)	1.000	.740
Zscore(Ti)	1.000	.811
Zscore(Zr)	1.000	.631

Extraction Method: Principal Component Analysis.

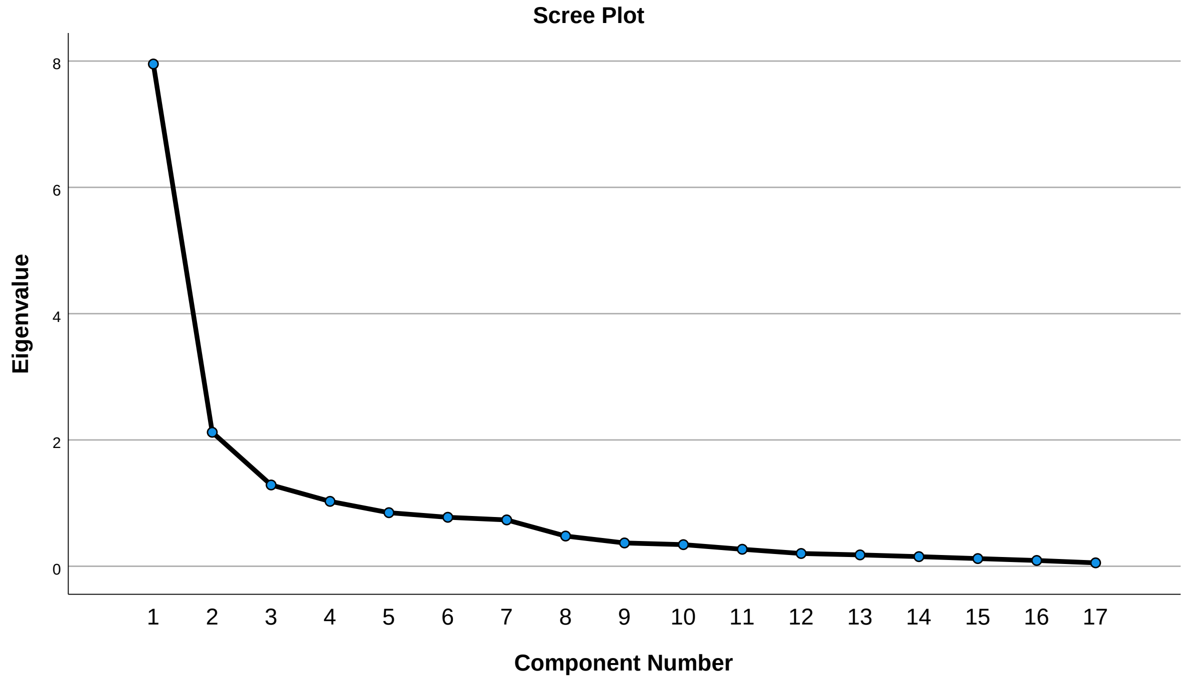
Total Variance Explained

Component	Initial Eigenvalues Total	% of Variance	Cumulative %	Extraction Sums of Squared .. Total	% of Variance
1	7.953	46.784	46.784	7.953	46.784
2	2.121	12.479	59.263	2.121	12.479
3	1.287	7.569	66.831	1.287	7.569
4	1.027	6.042	72.873	1.027	6.042
5	.848	4.989	77.862		
6	.775	4.559	82.421		
7	.733	4.314	86.735		
8	.478	2.811	89.546		
9	.369	2.168	91.714		
10	.342	2.010	93.724		
11	.268	1.579	95.303		
12	.202	1.187	96.489		
13	.179	1.054	97.543		
14	.152	.893	98.437		
15	.121	.712	99.148		
16	.091	.536	99.684		
17	.054	.316	100.000		

Total Variance Explained

Component	Extraction Sums .. Cumulative %
1	46.784
2	59.263
3	66.831
4	72.873
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	

Extraction Method: Principal Component Analysis.



Component Matrix[a]

	Component			
	1	2	3	4
Zscore(pH)	-.573	.020	.704	.127
Zscore(EC)	.710	-.112	-.610	-.009
Zscore(LOI)	.940	-.148	.030	.049
Zscore(Mag_Sus)	.822	-.076	.003	.118
Zscore(Al)	.443	.736	-.097	.097
Zscore(Ba)	.222	.497	.166	-.290
Zscore(Ca)	.867	-.085	.330	-.025
Zscore(Cr)	.511	.120	-.161	-.483
Zscore(Fe)	.888	-.086	.027	.063
Zscore(K)	.029	.906	-.093	.086
Zscore(P)	.783	.081	.203	-.075
Zscore(Rb)	.399	.477	.144	.131
Zscore(S)	.885	-.095	-.070	-.013
Zscore(Si)	-.708	.397	-.180	.295
Zscore(Sr)	.756	.060	.370	-.167
Zscore(Ti)	.848	.068	.029	.295
Zscore(Zr)	.411	-.178	-.001	.656

Extraction Method: Principal Component Analysis.

a. 4 components extracted.

Dunnicaer

Outliers

Factor Analysis

Outliers

Notes

Output Created		06-NOV-2022 15:27:26
Comments		
Input	Data	C:\Users\vanes\Documents\PhD\Analysis\SPSS\Combined (Geochemical and Elements)\Dunnicaer.sav
	Active Dataset	DataSet8
	Filter	<none>
	Weight	<none>
	Split File	<none>
	N of Rows in Working Data File	24
Missing Value Handling	Definition of Missing	User-defined missing values for dependent variables are treated as missing.
	Cases Used	Statistics are based on cases with no missing values for any dependent variable or factor used.
Syntax		EXAMINE VARIABLES=pH EC LOI MagSus Al Ba Ca Cl Cr Fe K Mn P Rb S Si Sr Ti V Zn Zr /PLOT BOXPLOT /COMPARE GROUPS /STATISTICS DESCRIPTIVES EXTREME /CINTERVAL 95 /MISSING LISTWISE...
Resources	Processor Time	00:00:06.42
	Elapsed Time	00:00:07.23

Extreme Values

			Case Number	Value
pH	Highest	1	1	5.50
		2	2	5.11
		3	9	5.01
		4	10	4.99
		5	17	4.95
	Lowest	1	20	4.17
		2	23	4.24
		3	22	4.37
		4	19	4.44
		5	4	4.45
EC	Highest	1	6	1543.00
		2	5	792.00
		3	1	778.00
		4	13	719.00
		5	7	676.00
	Lowest	1	21	247.00
		2	14	288.00
		3	24	312.00
		4	16	382.00
		5	22	386.00
LOI	Highest	1	23	12.97
		2	24	11.39
		3	13	11.37
		4	19	10.85
		5	3	10.63
	Lowest	1	16	4.37
		2	11	4.86
		3	9	5.81
		4	12	5.86
		5	10	6.37
MagSus	Highest	1	18	1186.33
		2	23	1012.99
		3	19	910.92
		4	24	578.15
		5	13	475.68
	Lowest	1	12	44.53
		2	3	63.93
		3	8	65.52

Extreme Values

			Case Number	Value
		4	4	71.82
		5	22	76.41
Al	Highest	1	16	7.51
		2	9	7.42
		3	21	7.26
		4	2	7.16
		5	15	7.04
	Lowest	1	3	5.28
		2	5	5.81
		3	6	6.00
		4	8	6.25
		5	19	6.27
Ba	Highest	1	10	.10
		2	18	.09
		3	6	.09
		4	1	.09
		5	23	.08
	Lowest	1	21	.05
		2	3	.05
		3	24	.06
		4	16	.06
		5	4	.07
Ca	Highest	1	6	2.32
		2	1	2.07
		3	10	2.02
		4	2	1.02
		5	18	1.00
	Lowest	1	22	.60
		2	3	.61
		3	23	.63
		4	24	.65
		5	7	.69
Cl	Highest	1	23	.10
		2	20	.08
		3	18	.08
		4	2	.06
		5	24	.06

Extreme Values

			Case Number	Value
	Lowest	1	9	.02
		2	12	.02
		3	14	.02
		4	10	.03
		5	21	.03
Cr	Highest	1	9	.02
		2	1	.01
		3	23	.01
		4	24	.01
		5	15	.01
	Lowest	1	16	.01
		2	18	.01
		3	7	.01
		4	5	.01
		5	3	.01
Fe	Highest	1	23	3.88
		2	18	3.76
		3	24	3.69
		4	19	3.56
		5	2	3.35
	Lowest	1	3	2.43
		2	6	2.60
		3	10	2.64
		4	11	2.65
		5	7	2.67
K	Highest	1	16	1.91
		2	9	1.89
		3	2	1.87
		4	12	1.86
		5	15	1.79
	Lowest	1	23	1.45
		2	5	1.54
		3	13	1.55
		4	3	1.56
		5	22	1.59
Mn	Highest	1	10	1.11
		2	6	.72
		3	23	.70

Extreme Values

			Case Number	Value
		4	18	.65
		5	1	.31
	Lowest	1	3	.02
		2	12	.06
		3	16	.08
		4	8	.08
		5	22	.09
P	Highest	1	18	1.12
		2	19	.87
		3	13	.87
		4	23	.78
		5	1	.78
	Lowest	1	16	.40
		2	11	.45
		3	7	.47
		4	15	.48
		5	3	.48
Rb	Highest	1	13	.01
		2	20	.01
		3	24	.01
		4	3	.01
		5	4	.01[a]
	Lowest	1	10	.01
		2	15	.01
		3	7	.01
		4	5	.01
		5	1	.01
S	Highest	1	24	.15
		2	23	.13
		3	13	.11
		4	20	.11
		5	19	.10
	Lowest	1	16	.04
		2	11	.05
		3	12	.06
		4	7	.06
		5	15	.06

Extreme Values

			Case Number	Value
Si	Highest	1	16	31.21
		2	11	31.13
		3	12	29.92
		4	9	29.21
		5	21	28.66
	Lowest	1	23	22.87
		2	19	24.19
		3	20	25.27
		4	5	25.37
		5	24	25.41
Sr	Highest	1	6	.03
		2	1	.03
		3	10	.03
		4	2	.02
		5	18	.02
	Lowest	1	3	.02
		2	11	.02
		3	23	.02
		4	22	.02
		5	7	.02
Ti	Highest	1	2	.55
		2	11	.55
		3	16	.54
		4	9	.54
		5	8	.53
	Lowest	1	23	.47
		2	19	.47
		3	24	.48
		4	5	.49
		5	18	.49
V	Highest	1	20	.01
		2	9	.01
		3	18	.01
		4	17	.01
		5	24	.01
	Lowest	1	22	.01
		2	8	.01
		3	6	.01

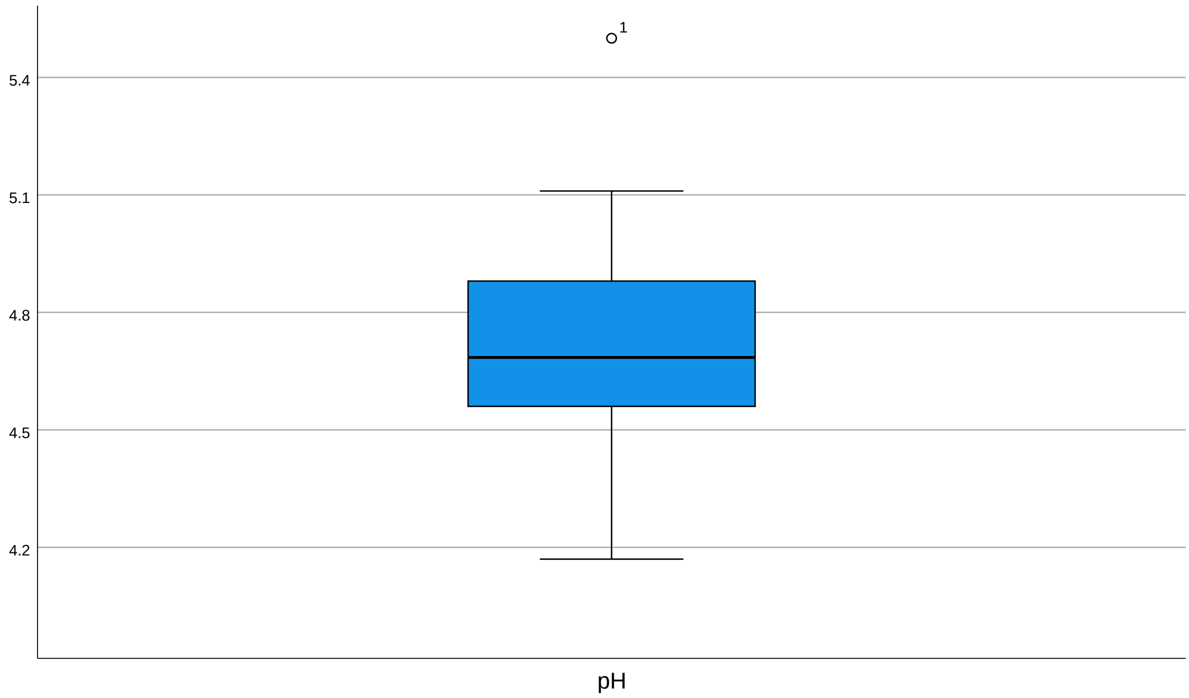
Extreme Values

			Case Number	Value
		4	14	.01
		5	13	.01
Zn	Highest	1	6	.05
		2	10	.04
		3	1	.02
		4	15	.02
		5	18	.02
	Lowest	1	22	.00
		2	3	.01
		3	21	.01
		4	14	.01
		5	24	.01
Zr	Highest	1	6	.02
		2	10	.02
		3	7	.02
		4	4	.02
		5	18	.02[b]
	Lowest	1	1	.02
		2	16	.02
		3	22	.02
		4	13	.02
		5	5	.02

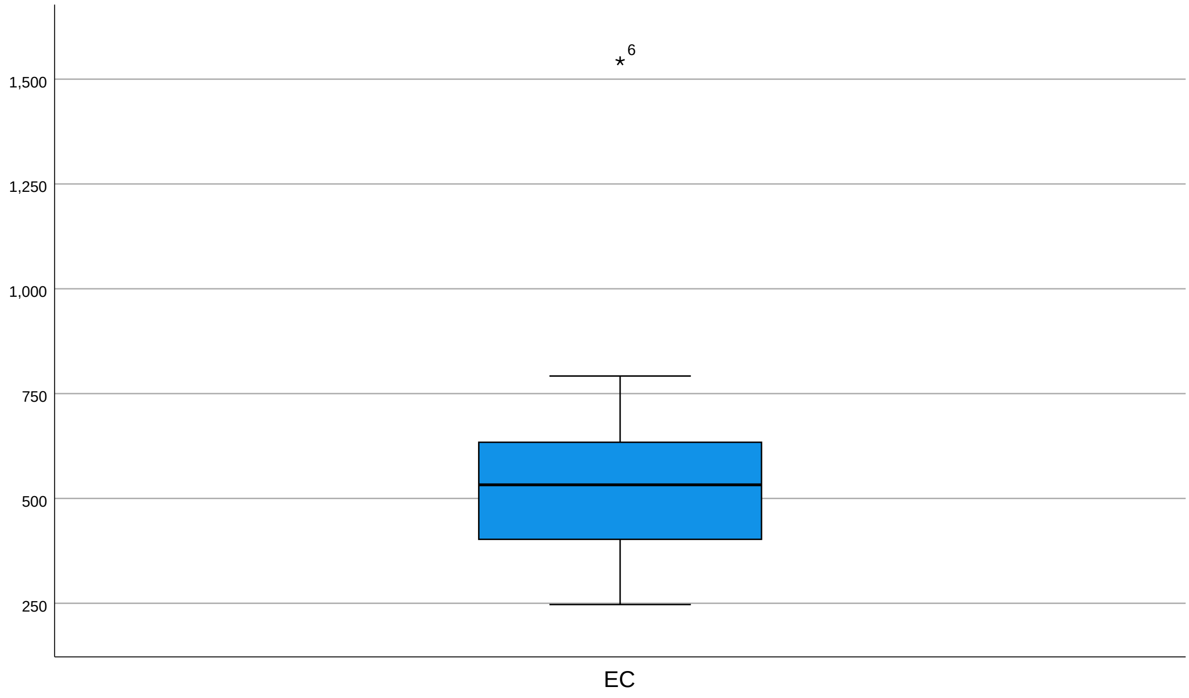
a. Only a partial list of cases with the value .01 are shown in the table of upper extremes.

b. Only a partial list of cases with the value .02 are shown in the table of upper extremes.

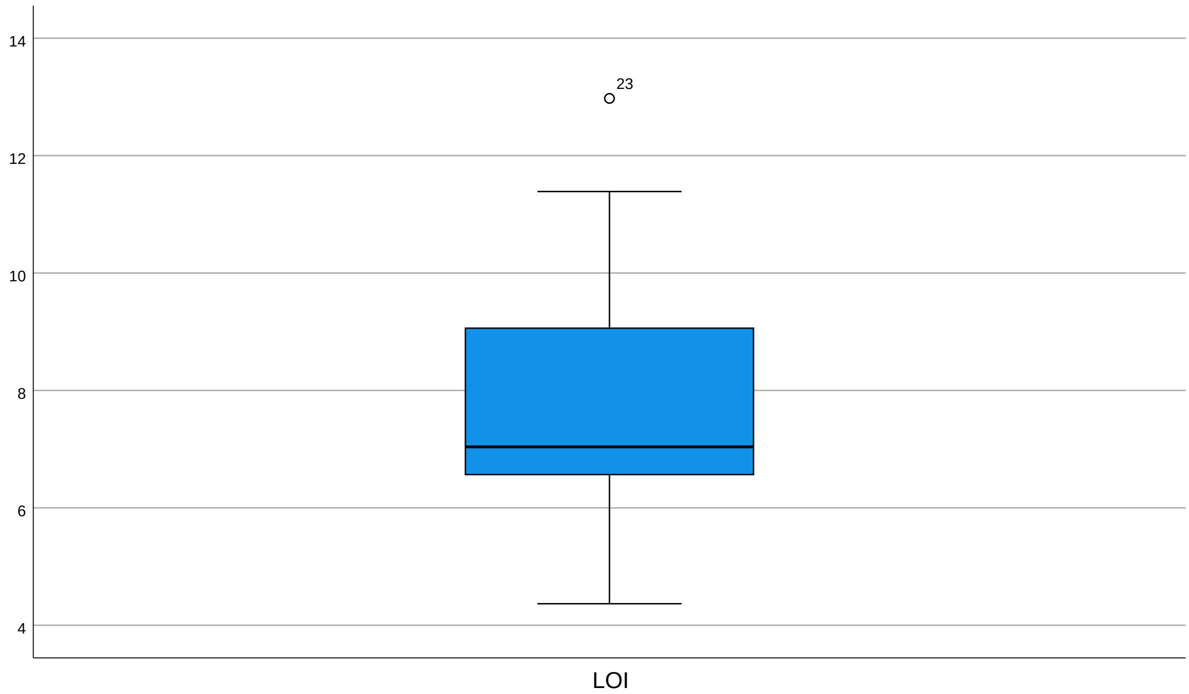
pH



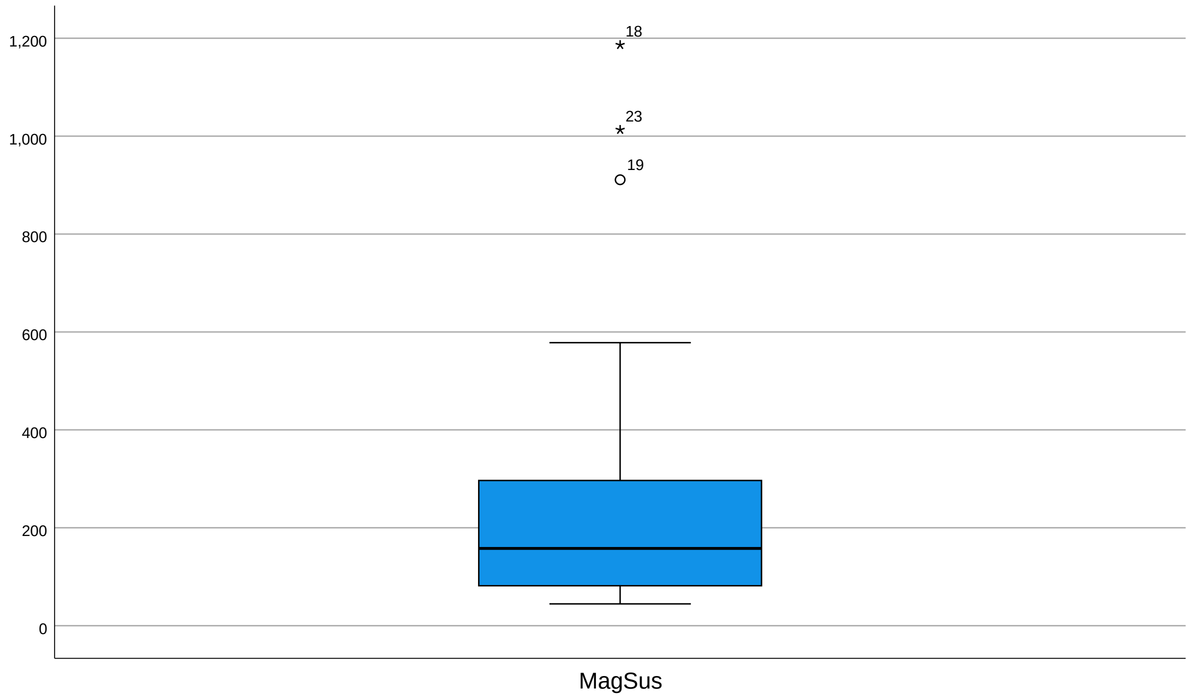
EC



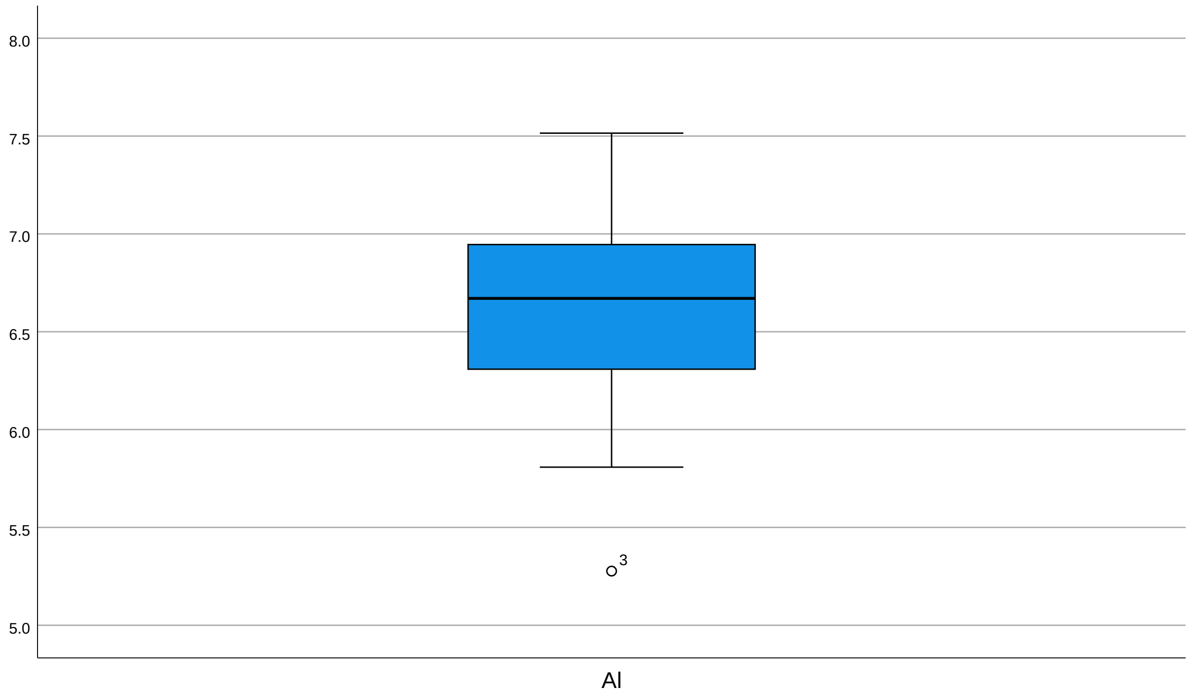
LOI



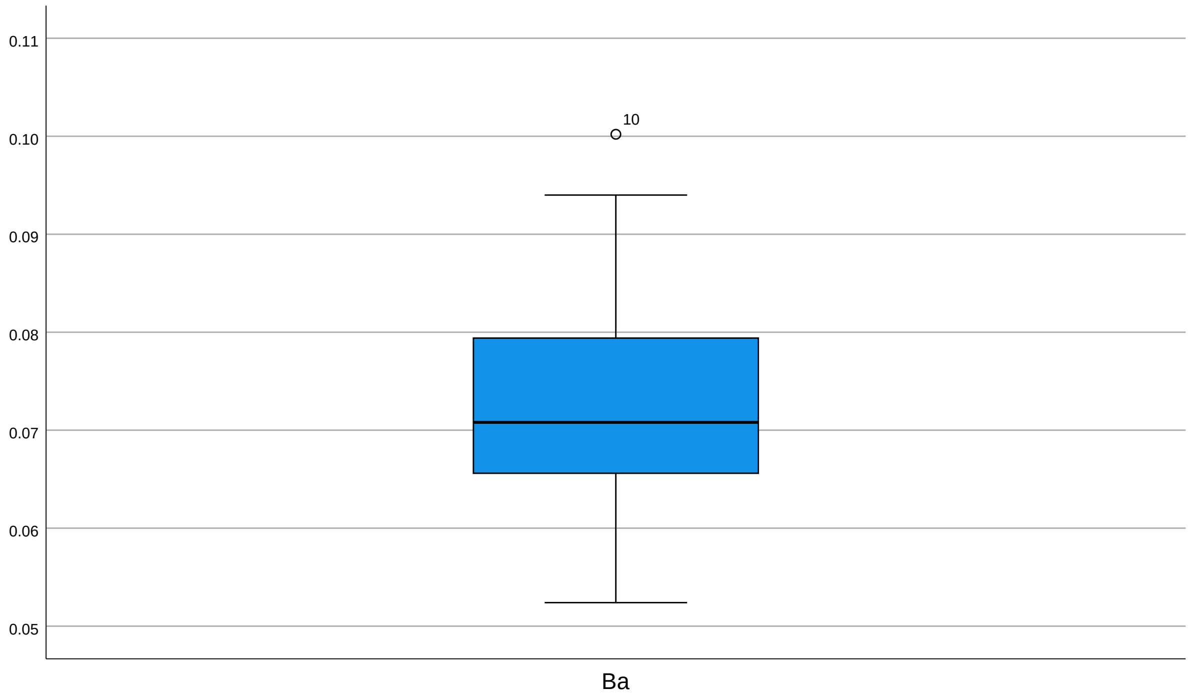
MagSus



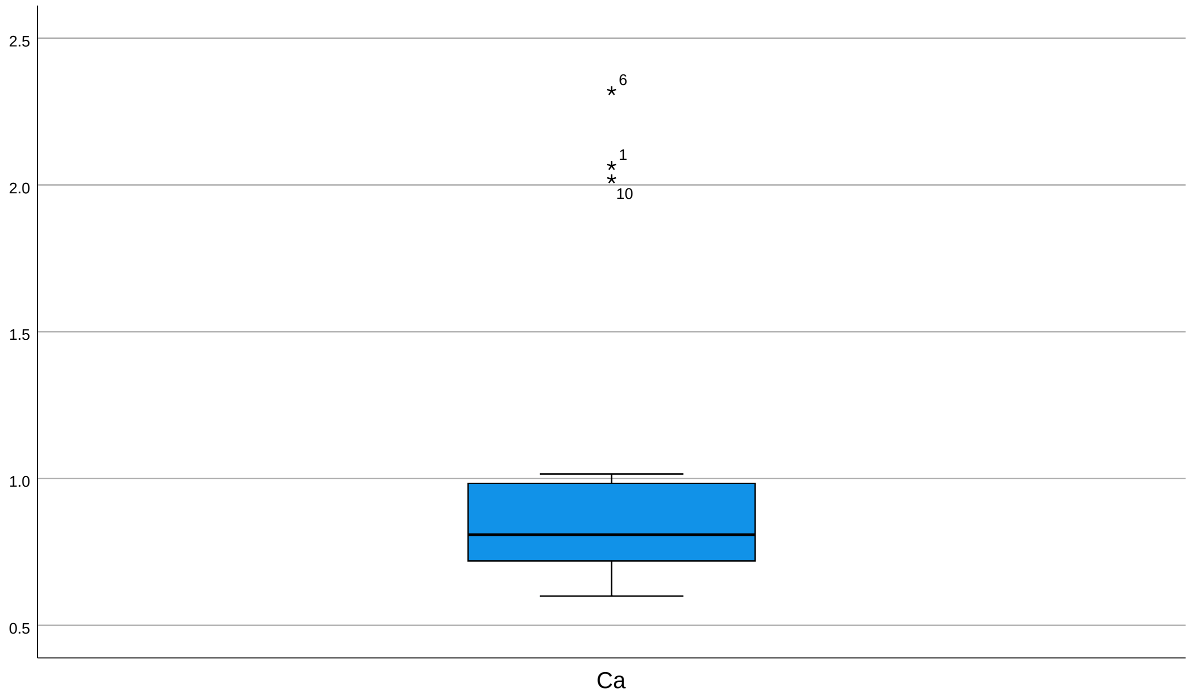
Al



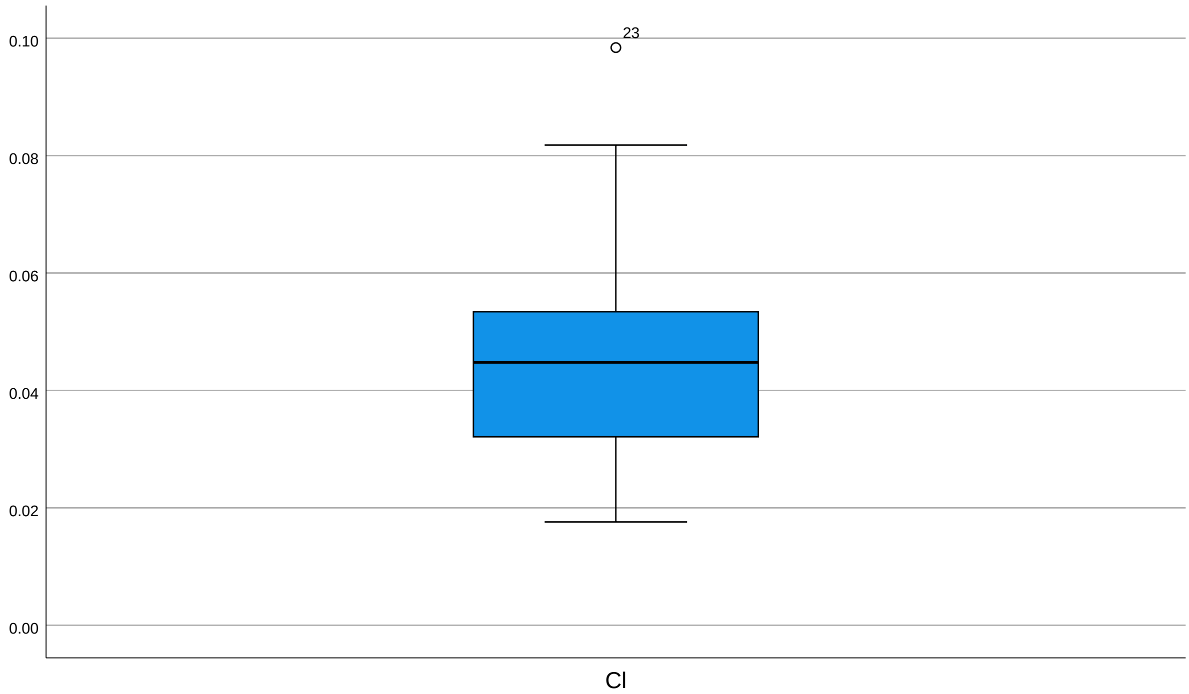
Ba



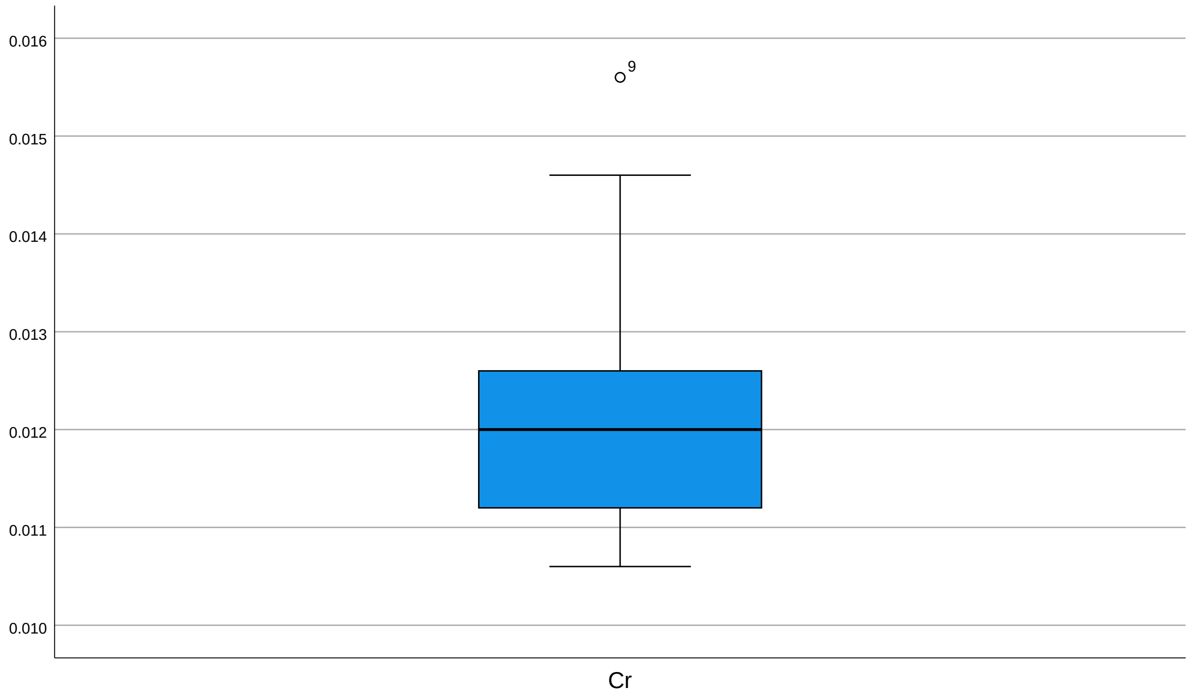
Ca



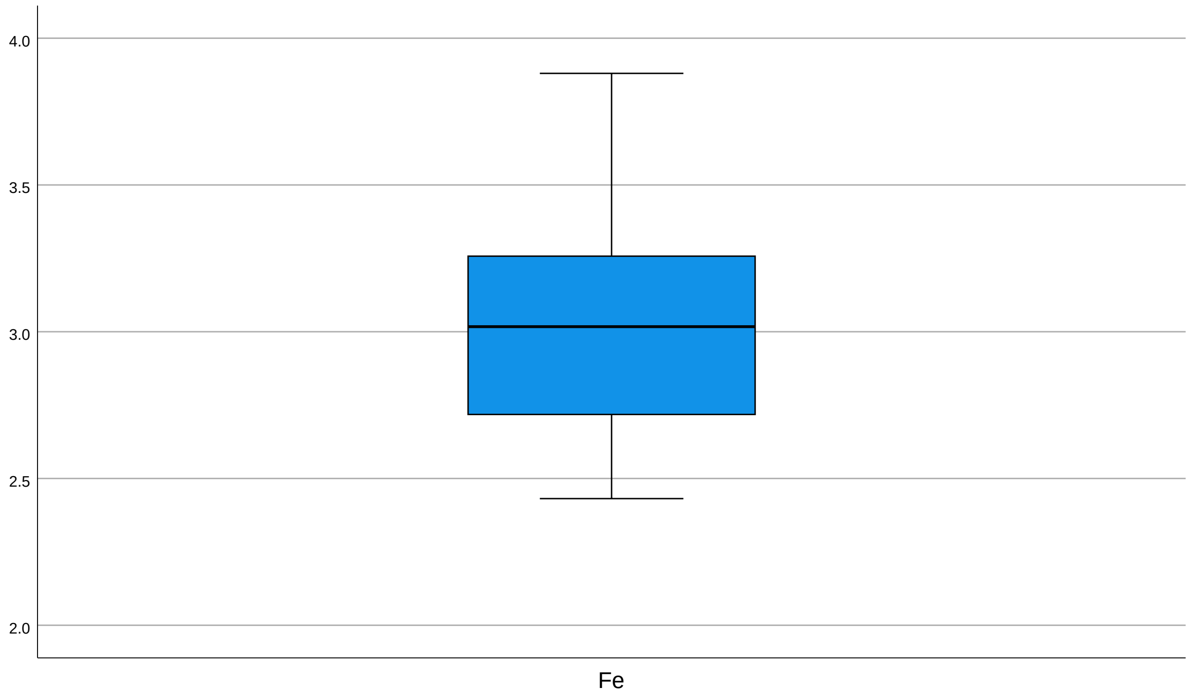
Cl



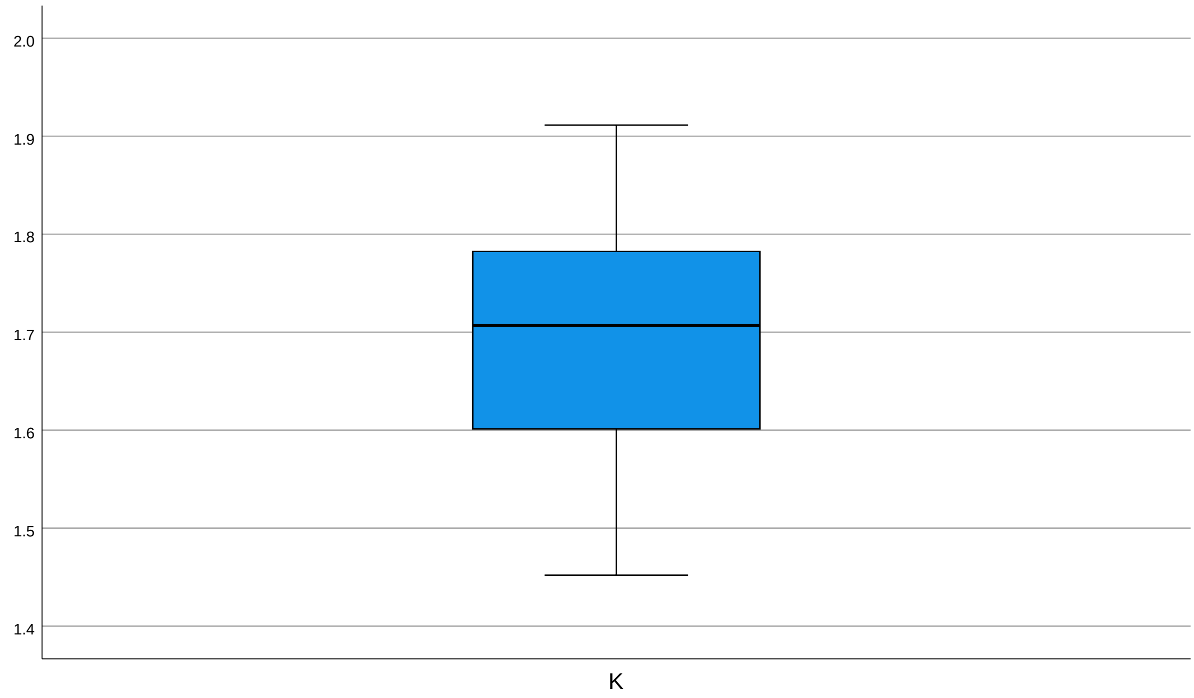
Cr



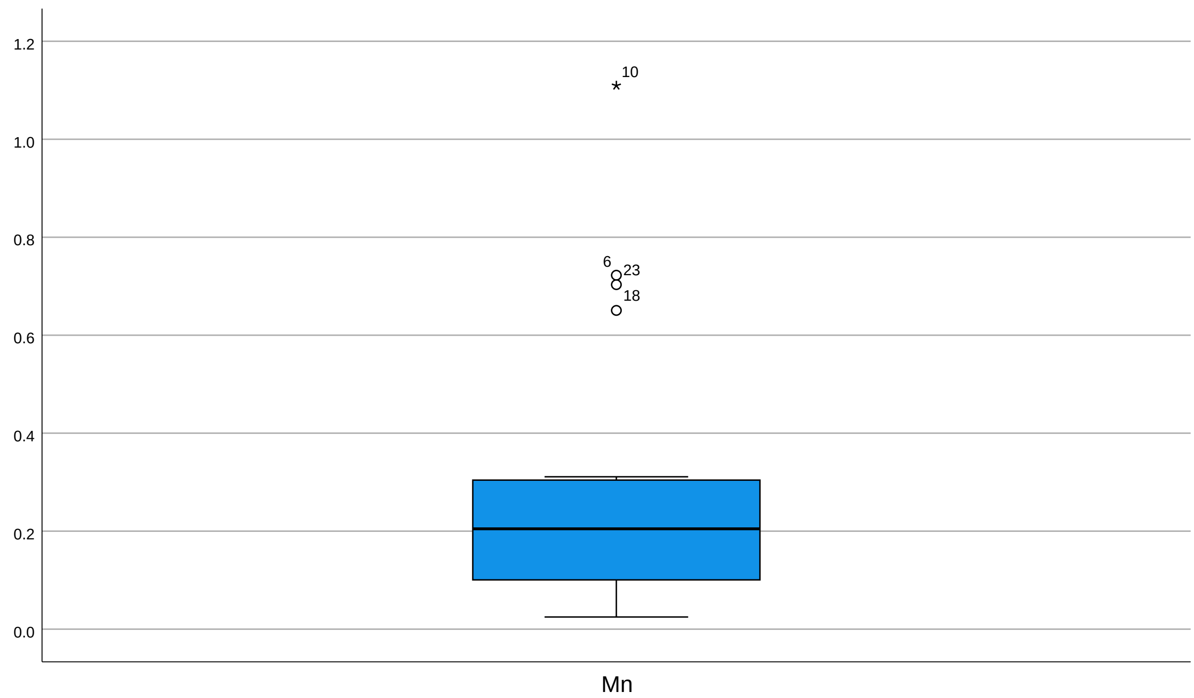
Fe



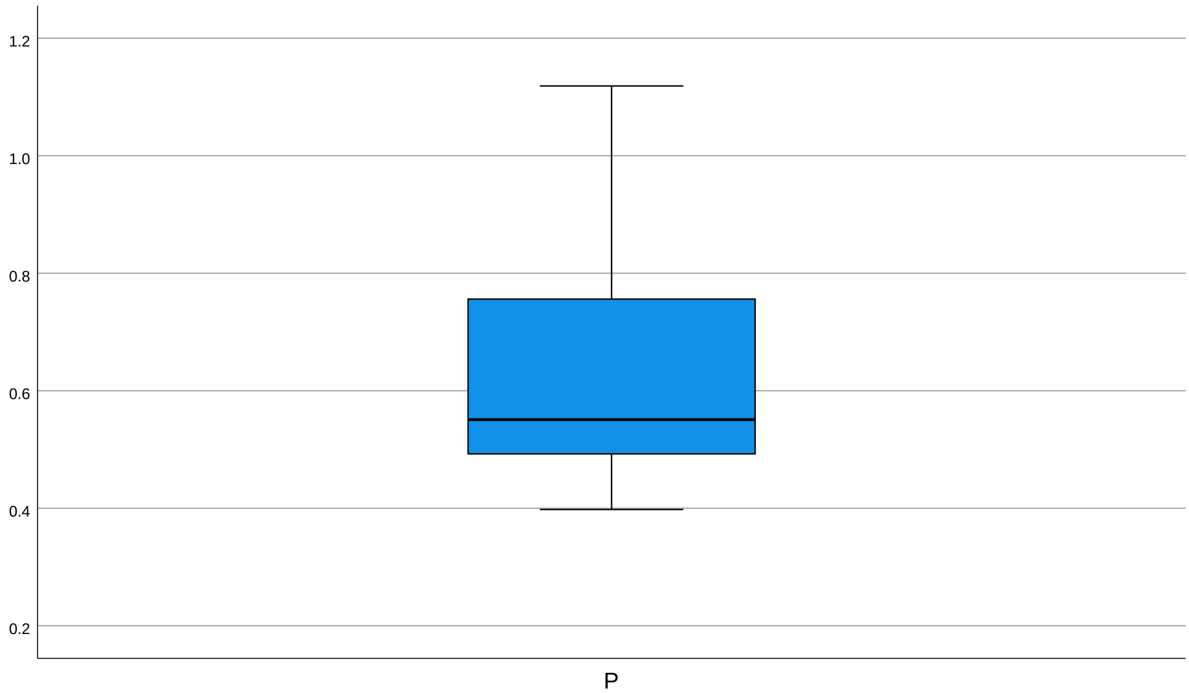
K



Mn



P



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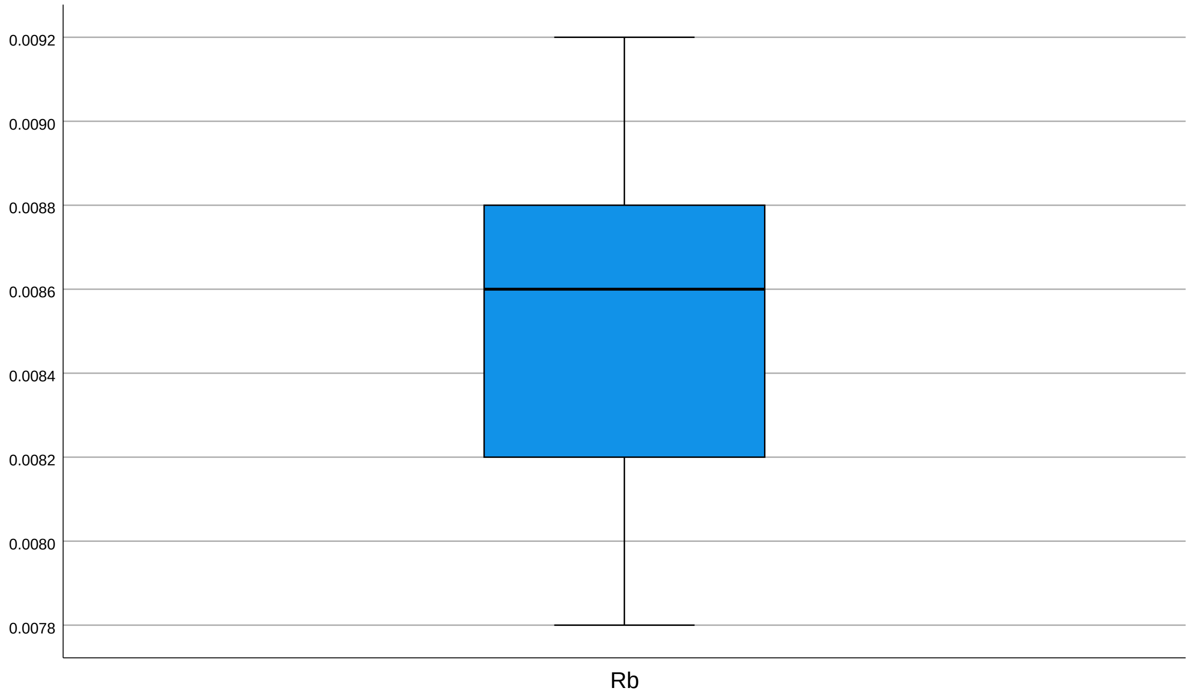
1.0
0.8
0.6
0.4
0.2
P

Rb



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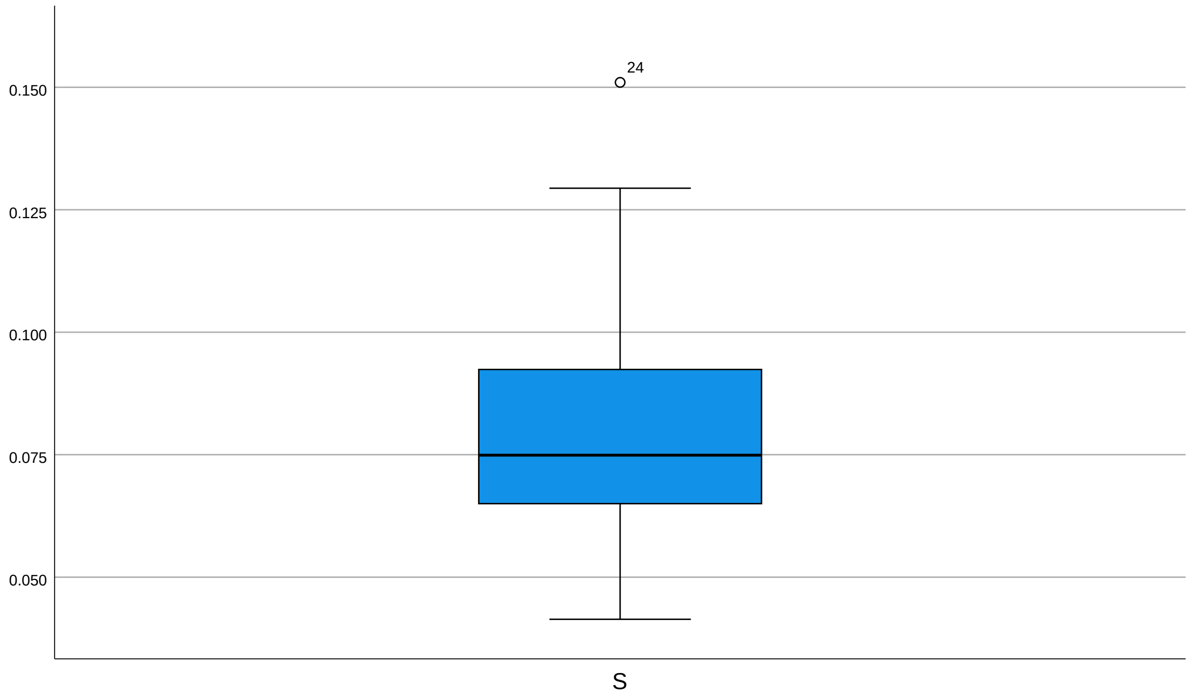
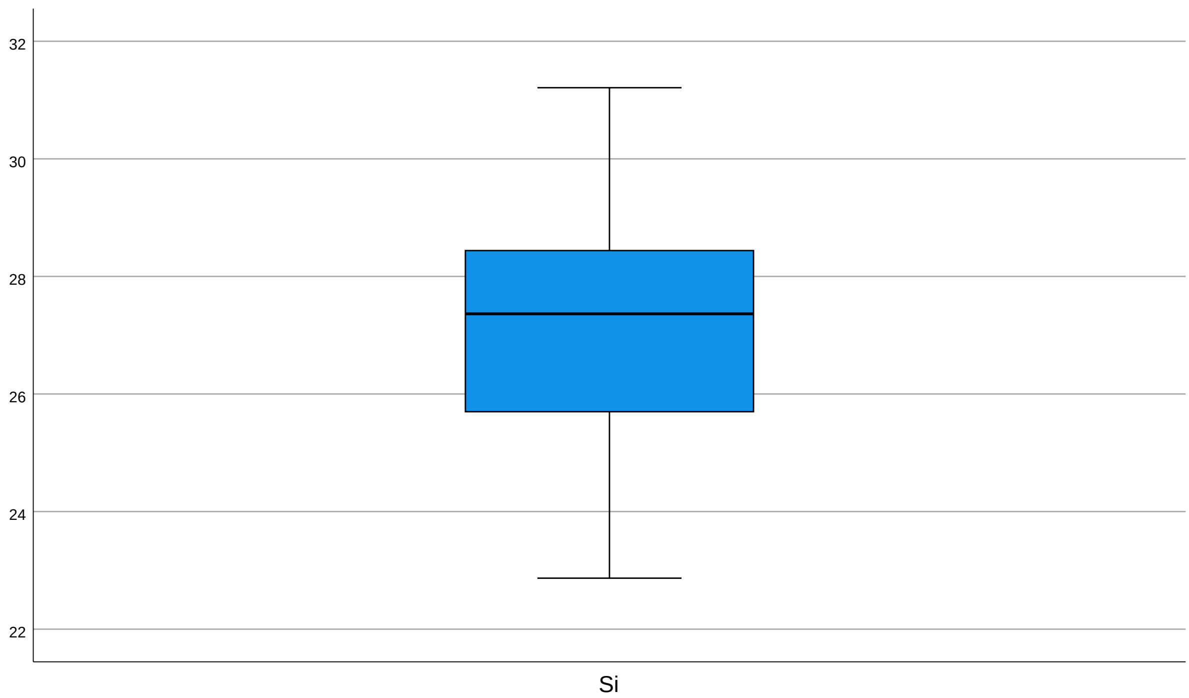
0.0090
0.0088
0.0086
0.0084
0.0082
0.0080
0.0078
Rb

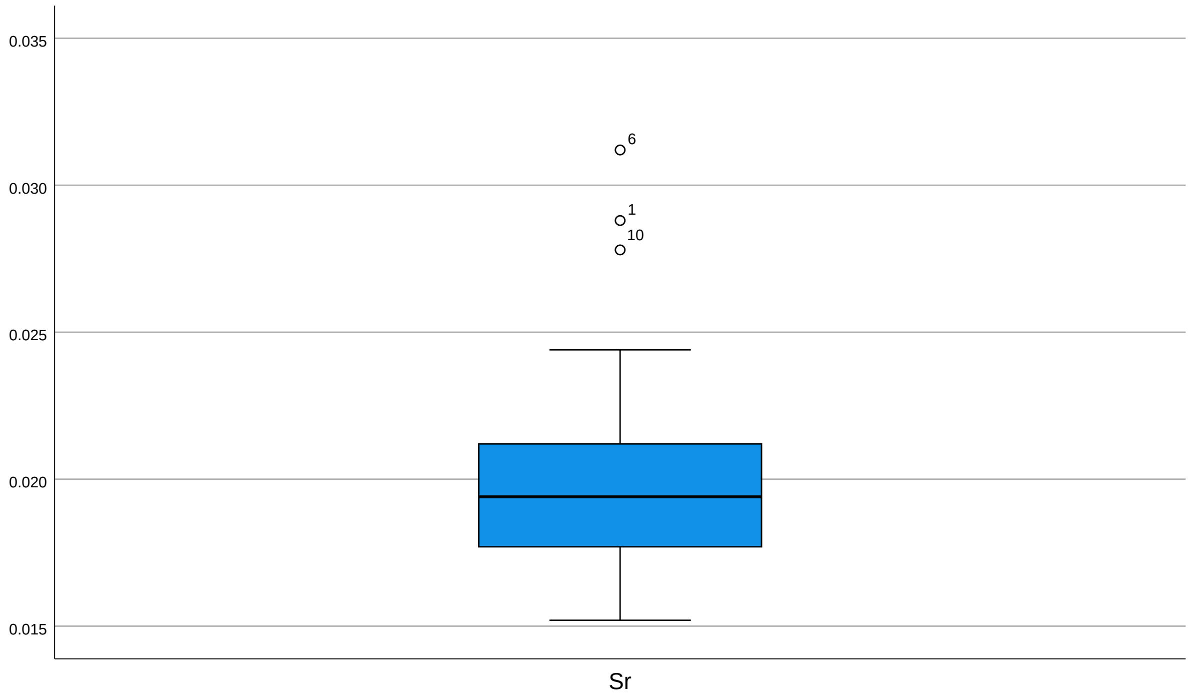
S



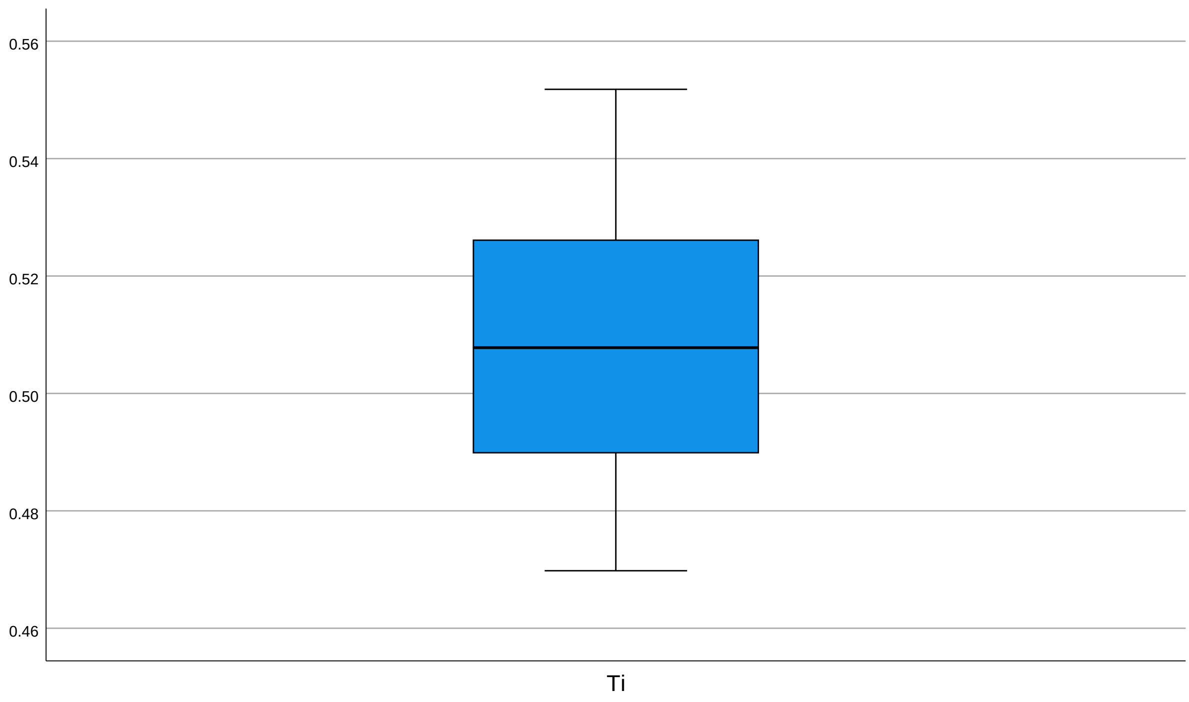
Si



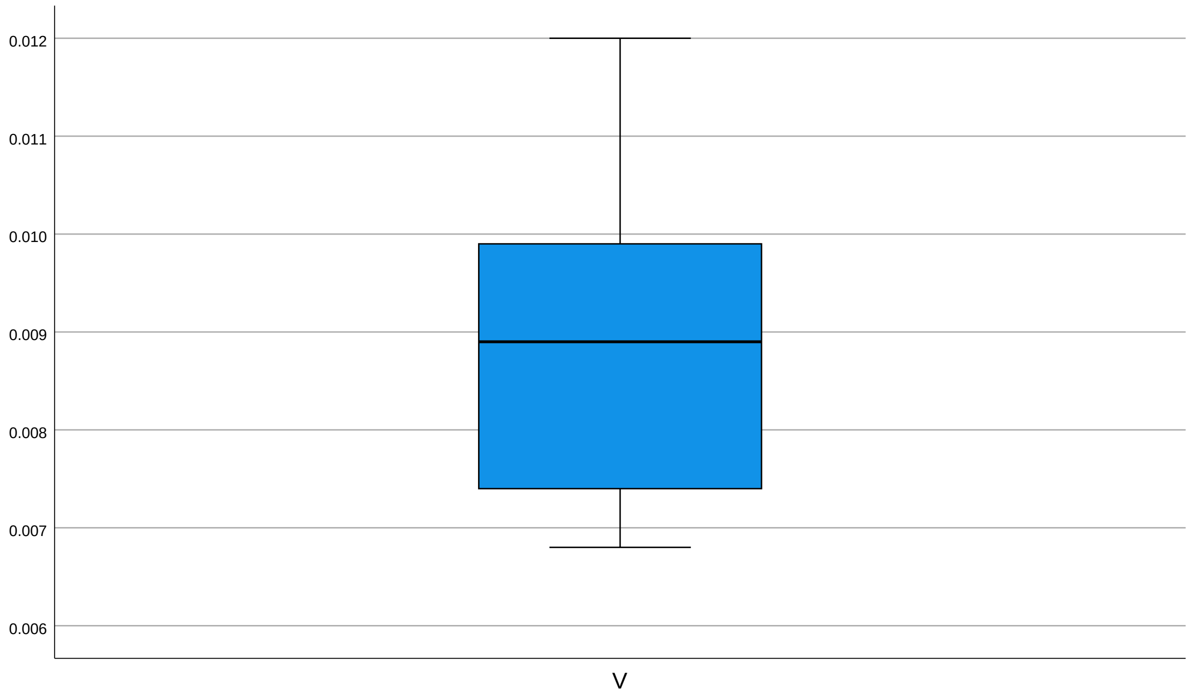
Sr



Ti



V



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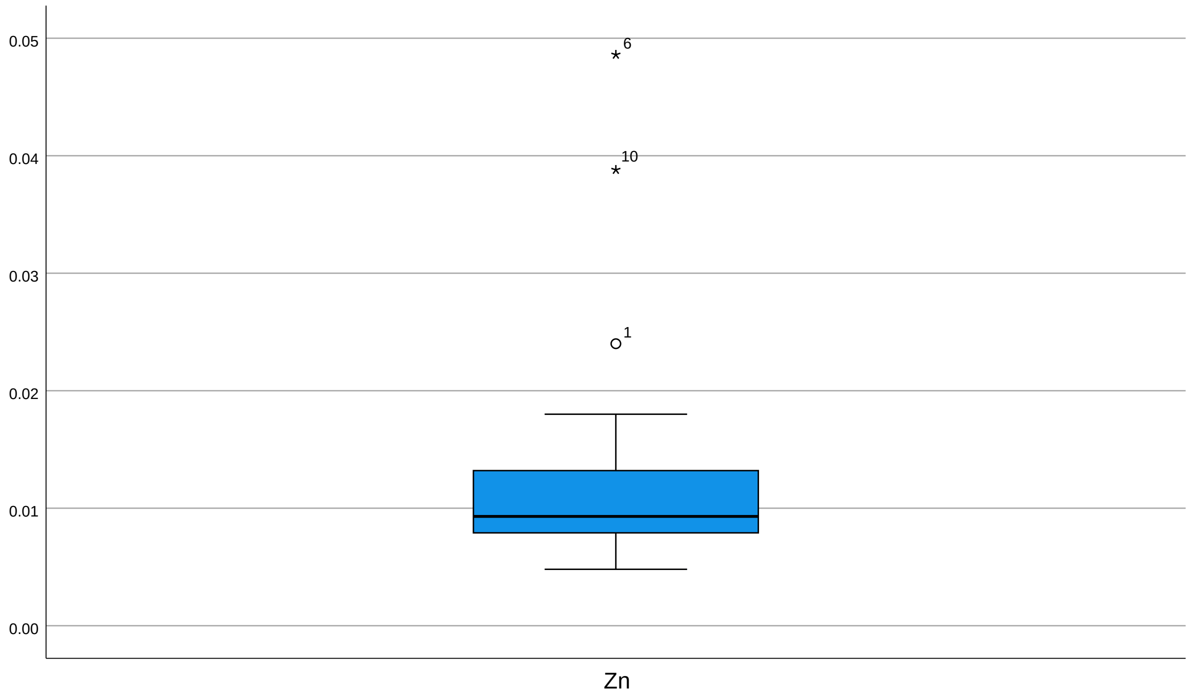
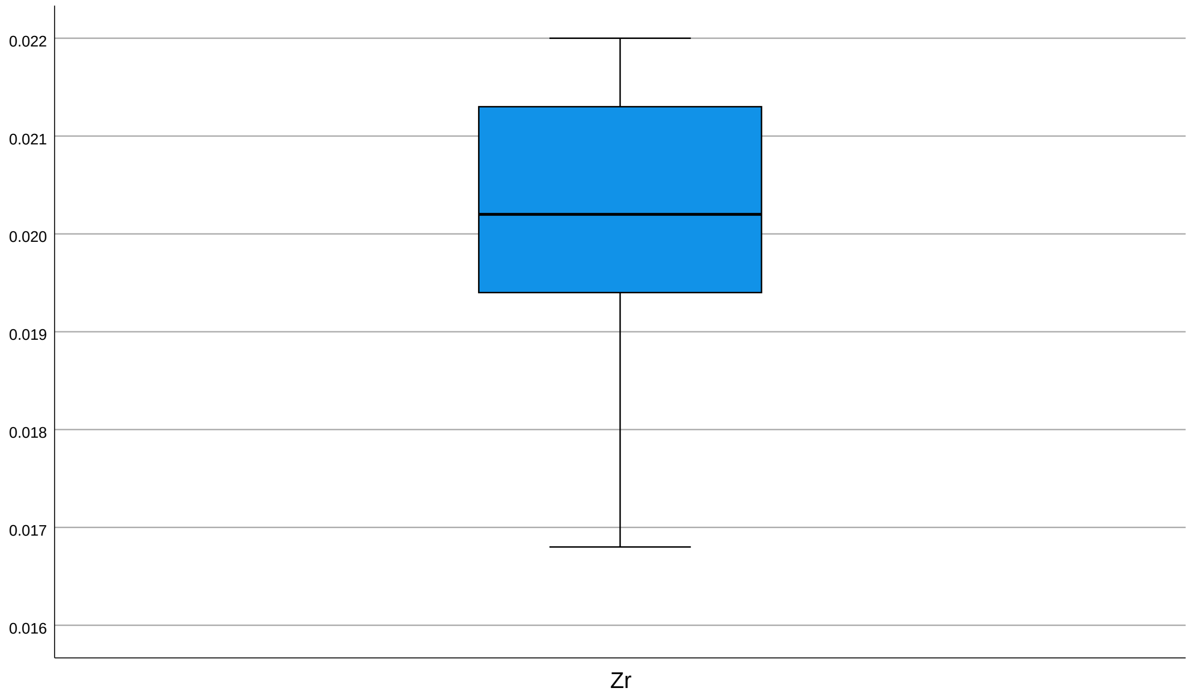
0.010
0.009
0.008
0.007
0.006
V

Zn



0.05
0.04
0.03
0.02
0.01
0.00
6
10
1
Zn

Zr



Factor Analysis

Notes

Output Created		06-NOV-2022 15:30:18
Comments		
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	N of Rows in Working Data File	24
Missing Value Handling	Definition of Missing	MISSING=EXCLUDE: User-defined missing values are treated as missing.
	Cases Used	LISTWISE: Statistics are based on cases with no missing values for any variable used.
Syntax		FACTOR /VARIABLES ZSco01 ZEC ZLOI ZMagSus ZSco02 ZSco03 ZCa ZSco04 ZCr ZSco05 ZSco06 ZMn ZP ZSco07 ZSco08 ZSco09 ZSr ZSco10 ZSco11 ZZn ZSco12 /MISSING LISTWISE /ANALYSIS ZSco01 ZEC ZLOI ZMagSus ZSco02 ZSco03 ZCa ZSco04 ZCr ZSco05 ZSco06 ZMn ZP ZSco07 ZSco08 ZSco09 ZSr ZSco10 ZSco11 ZZn ZSco12 /PRINT INITIAL CORRELATION SIG DET KMO EXTRACTION /PLOT EIGEN ROTATION /CRITERIA MINEIGEN (1) ITERATE(100) /EXTRACTION PC /ROTATION NOROTATE /METHOD=CORRELATIO...

Notes

Resources	Processor Time	00:00:00.70
	Elapsed Time	00:00:00.91
	Maximum Memory Required	53464 (52.211K) bytes

Correlation Matrix[a]

		Zscore(pH)	Zscore(EC)	Zscore(LOI)	Zscore (MagSus)
Correlation	Zscore(pH)	1.000	.107	-.559	-.353
	Zscore(EC)	.107	1.000	-.068	-.031
	Zscore(LOI)	-.559	-.068	1.000	.550
	Zscore(MagSus)	-.353	-.031	.550	1.000
	Zscore(Al)	.216	-.396	-.469	-.044
	Zscore(Ba)	.126	.474	.003	.442
	Zscore(Ca)	.506	.682	-.263	-.073
	Zscore(Cl)	-.611	.047	.590	.663
	Zscore(Cr)	.237	-.030	.091	.060
	Zscore(Fe)	-.218	-.269	.495	.776
	Zscore(K)	.437	-.133	-.817	-.490
	Zscore(Mn)	.041	.439	.121	.453
	Zscore(P)	-.165	.199	.437	.774
	Zscore(Rb)	-.439	-.362	.474	.122
	Zscore(S)	-.489	-.131	.903	.547
	Zscore(Si)	.342	-.195	-.836	-.574
	Zscore(Sr)	.560	.605	-.367	-.072
	Zscore(Ti)	.341	-.159	-.734	-.631
	Zscore(V)	-.107	-.250	.064	.427
	Zscore(Zn)	.254	.745	-.191	.038
	Zscore(Zr)	-.351	.110	-.024	.040
Sig. (1-tailed)	Zscore(pH)		.310	.002	.046
	Zscore(EC)	.310		.376	.442
	Zscore(LOI)	.002	.376		.003
	Zscore(MagSus)	.046	.442	.003	
	Zscore(Al)	.155	.028	.010	.419
	Zscore(Ba)	.279	.010	.495	.015
	Zscore(Ca)	.006	.000	.107	.368
	Zscore(Cl)	.001	.413	.001	.000
	Zscore(Cr)	.133	.445	.336	.390
	Zscore(Fe)	.153	.102	.007	.000
	Zscore(K)	.016	.267	.000	.008

Correlation Matrix[a]

		Zscore(Al)	Zscore(Ba)	Zscore(Ca)	Zscore(Cl)	Zscore(Cr)
Correlation	Zscore(pH)	.216	.126	.506	-.611	.237
	Zscore(EC)	-.396	.474	.682	.047	-.030
	Zscore(LOI)	-.469	.003	-.263	.590	.091
	Zscore(MagSus)	-.044	.442	-.073	.663	.060
	Zscore(Al)	1.000	-.030	-.077	-.193	.262
	Zscore(Ba)	-.030	1.000	.682	.136	.226
	Zscore(Ca)	-.077	.682	1.000	-.267	.198
	Zscore(Cl)	-.193	.136	-.267	1.000	-.132
	Zscore(Cr)	.262	.226	.198	-.132	1.000
	Zscore(Fe)	.266	.187	-.221	.585	.306
	Zscore(K)	.724	-.133	.101	-.501	.132
	Zscore(Mn)	-.056	.847	.658	.191	.156
	Zscore(P)	-.149	.703	.346	.441	.085
	Zscore(Rb)	.008	-.392	-.522	.200	.009
	Zscore(S)	-.240	-.002	-.202	.570	.173
	Zscore(Si)	.563	-.253	-.065	-.621	-.122
	Zscore(Sr)	.120	.616	.939	-.238	.148
	Zscore(Ti)	.505	-.363	-.162	-.365	-.057
	Zscore(V)	.507	-.027	-.256	.369	.318
	Zscore(Zn)	-.111	.728	.929	-.133	.090
	Zscore(Zr)	-.099	.091	-.024	.080	-.220
Sig. (1-tailed)	Zscore(pH)	.155	.279	.006	.001	.133
	Zscore(EC)	.028	.010	.000	.413	.445
	Zscore(LOI)	.010	.495	.107	.001	.336
	Zscore(MagSus)	.419	.015	.368	.000	.390
	Zscore(Al)		.445	.361	.184	.108
	Zscore(Ba)	.445		.000	.264	.144
	Zscore(Ca)	.361	.000		.104	.177
	Zscore(Cl)	.184	.264	.104		.269
	Zscore(Cr)	.108	.144	.177	.269	
	Zscore(Fe)	.104	.190	.149	.001	.073
	Zscore(K)	.000	.267	.320	.006	.269

Correlation Matrix[a]

		Zscore(Fe)	Zscore(K)	Zscore(Mn)	Zscore(P)	Zscore(Rb)
Correlation	Zscore(pH)	-.218	.437	.041	-.165	-.439
	Zscore(EC)	-.269	-.133	.439	.199	-.362
	Zscore(LOI)	.495	-.817	.121	.437	.474
	Zscore(MagSus)	.776	-.490	.453	.774	.122
	Zscore(Al)	.266	.724	-.056	-.149	.008
	Zscore(Ba)	.187	-.133	.847	.703	-.392
	Zscore(Ca)	-.221	.101	.658	.346	-.522
	Zscore(Cl)	.585	-.501	.191	.441	.200
	Zscore(Cr)	.306	.132	.156	.085	.009
	Zscore(Fe)	1.000	-.237	.191	.565	.251
	Zscore(K)	-.237	1.000	-.285	-.451	-.112
	Zscore(Mn)	.191	-.285	1.000	.624	-.369
	Zscore(P)	.565	-.451	.624	1.000	.065
	Zscore(Rb)	.251	-.112	-.369	.065	1.000
	Zscore(S)	.623	-.705	.185	.500	.475
	Zscore(Si)	-.521	.770	-.296	-.578	-.106
	Zscore(Sr)	-.092	.257	.594	.298	-.560
	Zscore(Ti)	-.416	.787	-.493	-.663	-.120
	Zscore(V)	.637	.232	-.027	.171	.142
	Zscore(Zn)	-.208	.024	.773	.347	-.525
	Zscore(Zr)	-.150	-.033	.309	-.033	-.003
Sig. (1-tailed)	Zscore(pH)	.153	.016	.425	.220	.016
	Zscore(EC)	.102	.267	.016	.176	.041
	Zscore(LOI)	.007	.000	.287	.016	.010
	Zscore(MagSus)	.000	.008	.013	.000	.285
	Zscore(Al)	.104	.000	.398	.243	.486
	Zscore(Ba)	.190	.267	.000	.000	.029
	Zscore(Ca)	.149	.320	.000	.049	.004
	Zscore(Cl)	.001	.006	.185	.015	.174
	Zscore(Cr)	.073	.269	.233	.347	.483
	Zscore(Fe)		.133	.186	.002	.119
	Zscore(K)	.133		.089	.014	.301

Correlation Matrix[a]

		Zscore(S)	Zscore(Si)	Zscore(Sr)	Zscore(Ti)	Zscore(V)
Correlation	Zscore(pH)	-.489	.342	.560	.341	-.107
	Zscore(EC)	-.131	-.195	.605	-.159	-.250
	Zscore(LOI)	.903	-.836	-.367	-.734	.064
	Zscore(MagSus)	.547	-.574	-.072	-.631	.427
	Zscore(Al)	-.240	.563	.120	.505	.507
	Zscore(Ba)	-.002	-.253	.616	-.363	-.027
	Zscore(Ca)	-.202	-.065	.939	-.162	-.256
	Zscore(Cl)	.570	-.621	-.238	-.365	.369
	Zscore(Cr)	.173	-.122	.148	-.057	.318
	Zscore(Fe)	.623	-.521	-.092	-.416	.637
	Zscore(K)	-.705	.770	.257	.787	.232
	Zscore(Mn)	.185	-.296	.594	-.493	-.027
	Zscore(P)	.500	-.578	.298	-.663	.171
	Zscore(Rb)	.475	-.106	-.560	-.120	.142
	Zscore(S)	1.000	-.743	-.238	-.700	.186
	Zscore(Si)	-.743	1.000	-.001	.808	-.152
	Zscore(Sr)	-.238	-.001	1.000	-.053	-.073
	Zscore(Ti)	-.700	.808	-.053	1.000	-.015
	Zscore(V)	.186	-.152	-.073	-.015	1.000
	Zscore(Zn)	-.150	-.085	.859	-.230	-.252
	Zscore(Zr)	.043	.126	-.069	-.104	-.082
Sig. (1-tailed)	Zscore(pH)	.008	.051	.002	.051	.309
	Zscore(EC)	.271	.180	.001	.229	.120
	Zscore(LOI)	.000	.000	.039	.000	.383
	Zscore(MagSus)	.003	.002	.369	.000	.019
	Zscore(Al)	.129	.002	.288	.006	.006
	Zscore(Ba)	.496	.116	.001	.041	.451
	Zscore(Ca)	.172	.382	.000	.224	.114
	Zscore(Cl)	.002	.001	.132	.040	.038
	Zscore(Cr)	.209	.285	.245	.395	.065
	Zscore(Fe)	.001	.005	.335	.022	.000
	Zscore(K)	.000	.000	.113	.000	.137

Correlation Matrix[a]

		Zscore(Zn)	Zscore(Zr)
Correlation	Zscore(pH)	.254	-.351
	Zscore(EC)	.745	.110
	Zscore(LOI)	-.191	-.024
	Zscore(MagSus)	.038	.040
	Zscore(Al)	-.111	-.099
	Zscore(Ba)	.728	.091
	Zscore(Ca)	.929	-.024
	Zscore(Cl)	-.133	.080
	Zscore(Cr)	.090	-.220
	Zscore(Fe)	-.208	-.150
	Zscore(K)	.024	-.033
	Zscore(Mn)	.773	.309
	Zscore(P)	.347	-.033
	Zscore(Rb)	-.525	-.003
	Zscore(S)	-.150	.043
	Zscore(Si)	-.085	.126
	Zscore(Sr)	.859	-.069
	Zscore(Ti)	-.230	-.104
	Zscore(V)	-.252	-.082
	Zscore(Zn)	1.000	.249
	Zscore(Zr)	.249	1.000
Sig. (1-tailed)	Zscore(pH)	.115	.046
	Zscore(EC)	.000	.304
	Zscore(LOI)	.186	.455
	Zscore(MagSus)	.429	.425
	Zscore(Al)	.304	.322
	Zscore(Ba)	.000	.336
	Zscore(Ca)	.000	.456
	Zscore(Cl)	.268	.356
	Zscore(Cr)	.337	.150
	Zscore(Fe)	.165	.242
	Zscore(K)	.456	.440

Correlation Matrix[a]

	Zscore(pH)	Zscore(EC)	Zscore(LOI)	Zscore (MagSus)
Zscore(Mn)	.425	.016	.287	.013
Zscore(P)	.220	.176	.016	.000
Zscore(Rb)	.016	.041	.010	.285
Zscore(S)	.008	.271	.000	.003
Zscore(Si)	.051	.180	.000	.002
Zscore(Sr)	.002	.001	.039	.369
Zscore(Ti)	.051	.229	.000	.000
Zscore(V)	.309	.120	.383	.019
Zscore(Zn)	.115	.000	.186	.429
Zscore(Zr)	.046	.304	.455	.425

Correlation Matrix[a]

	Zscore(Al)	Zscore(Ba)	Zscore(Ca)	Zscore(Cl)	Zscore(Cr)
Zscore(Mn)	.398	.000	.000	.185	.233
Zscore(P)	.243	.000	.049	.015	.347
Zscore(Rb)	.486	.029	.004	.174	.483
Zscore(S)	.129	.496	.172	.002	.209
Zscore(Si)	.002	.116	.382	.001	.285
Zscore(Sr)	.288	.001	.000	.132	.245
Zscore(Ti)	.006	.041	.224	.040	.395
Zscore(V)	.006	.451	.114	.038	.065
Zscore(Zn)	.304	.000	.000	.268	.337
Zscore(Zr)	.322	.336	.456	.356	.150

Correlation Matrix[a]

	Zscore(Fe)	Zscore(K)	Zscore(Mn)	Zscore(P)	Zscore(Rb)
Zscore(Mn)	.186	.089		.001	.038
Zscore(P)	.002	.014	.001		.382
Zscore(Rb)	.119	.301	.038	.382	
Zscore(S)	.001	.000	.193	.006	.009
Zscore(Si)	.005	.000	.080	.002	.310
Zscore(Sr)	.335	.113	.001	.078	.002
Zscore(Ti)	.022	.000	.007	.000	.288
Zscore(V)	.000	.137	.449	.212	.254
Zscore(Zn)	.165	.456	.000	.048	.004
Zscore(Zr)	.242	.440	.071	.439	.495

Correlation Matrix[a]

	Zscore(S)	Zscore(Si)	Zscore(Sr)	Zscore(Ti)	Zscore(V)
Zscore(Mn)	.193	.080	.001	.007	.449
Zscore(P)	.006	.002	.078	.000	.212
Zscore(Rb)	.009	.310	.002	.288	.254
Zscore(S)		.000	.131	.000	.192
Zscore(Si)	.000		.498	.000	.239
Zscore(Sr)	.131	.498		.403	.367
Zscore(Ti)	.000	.000	.403		.472
Zscore(V)	.192	.239	.367	.472	
Zscore(Zn)	.242	.347	.000	.140	.118
Zscore(Zr)	.422	.278	.375	.315	.351

Correlation Matrix[a]

	Zscore(Zn)	Zscore(Zr)
Zscore(Mn)	.000	.071
Zscore(P)	.048	.439
Zscore(Rb)	.004	.495
Zscore(S)	.242	.422
Zscore(Si)	.347	.278
Zscore(Sr)	.000	.375
Zscore(Ti)	.140	.315
Zscore(V)	.118	.351
Zscore(Zn)		.120
Zscore(Zr)	.120	

a. Determinant = 1.063E-17

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.334
Bartlett's Test of Sphericity	Approx. Chi-Square	592.755
	df	210
	Sig.	.000

Communalities

	Initial	Extraction
Zscore(pH)	1.000	.766
Zscore(EC)	1.000	.627
Zscore(LOI)	1.000	.923
Zscore(MagSus)	1.000	.828
Zscore(Al)	1.000	.868
Zscore(Ba)	1.000	.820
Zscore(Ca)	1.000	.948
Zscore(Cl)	1.000	.670
Zscore(Cr)	1.000	.499
Zscore(Fe)	1.000	.895
Zscore(K)	1.000	.904
Zscore(Mn)	1.000	.856
Zscore(P)	1.000	.771
Zscore(Rb)	1.000	.478
Zscore(S)	1.000	.804
Zscore(Si)	1.000	.882
Zscore(Sr)	1.000	.885
Zscore(Ti)	1.000	.813
Zscore(V)	1.000	.721
Zscore(Zn)	1.000	.934
Zscore(Zr)	1.000	.678

Extraction Method: Principal Component Analysis.

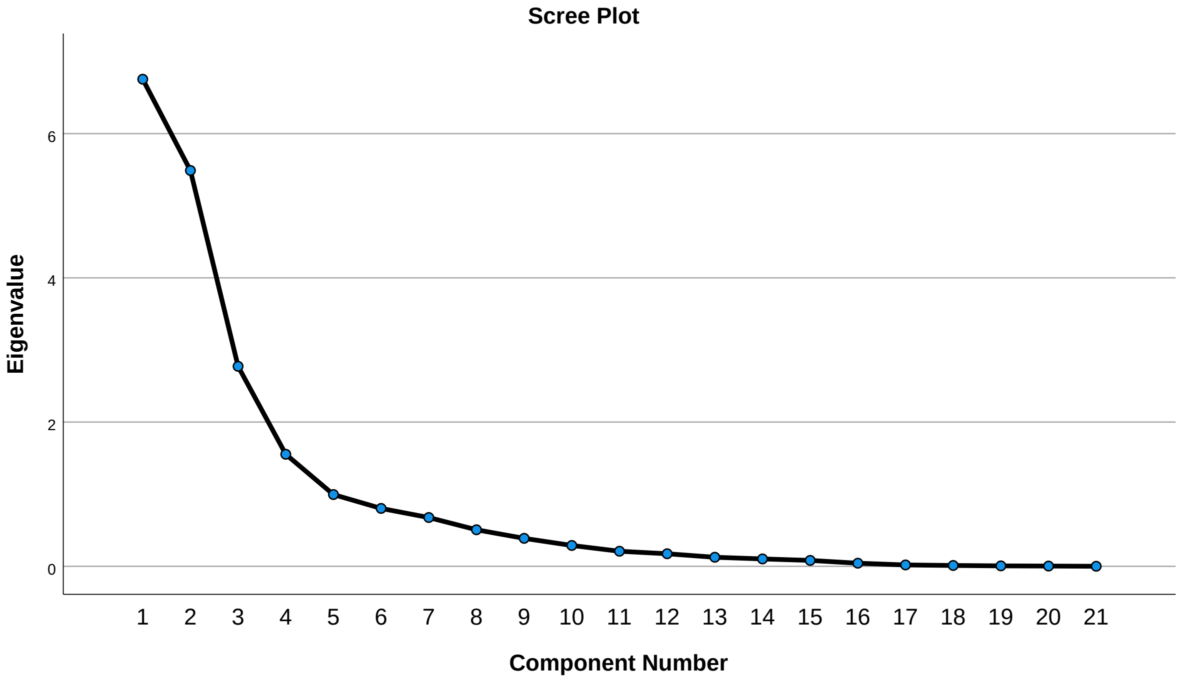
Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared ..	
	Total	% of Variance	Cumulative %	Total	% of Variance
1	6.755	32.165	32.165	6.755	32.165
2	5.489	26.136	58.300	5.489	26.136
3	2.773	13.204	71.505	2.773	13.204
4	1.553	7.397	78.901	1.553	7.397
5	.995	4.738	83.639		
6	.803	3.822	87.461		
7	.676	3.221	90.682		
8	.507	2.413	93.094		
9	.387	1.845	94.940		
10	.289	1.375	96.314		
11	.209	.994	97.309		
12	.174	.828	98.137		
13	.125	.596	98.733		
14	.102	.486	99.219		
15	.082	.389	99.608		
16	.043	.204	99.812		
17	.019	.089	99.902		
18	.011	.053	99.955		
19	.006	.028	99.983		
20	.003	.015	99.998		
21	.000	.002	100.000		

Total Variance Explained

Component	Extraction Sums .. Cumulative %
1	32.165
2	58.300
3	71.505
4	78.901
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	
20	
21	

Extraction Method: Principal Component Analysis.



Component Matrix[a]

	Component			
	1	2	3	4
Zscore(pH)	-.550	.425	.231	-.480
Zscore(EC)	.061	.719	-.325	.026
Zscore(LOI)	.886	-.250	-.184	-.205
Zscore(MagSus)	.809	.069	.358	.201
Zscore(Al)	-.401	-.108	.809	.204
Zscore(Ba)	.315	.809	.212	.143
Zscore(Ca)	-.085	.957	-.001	-.157
Zscore(Cl)	.738	-.169	.092	.295
Zscore(Cr)	.072	.145	.518	-.452
Zscore(Fe)	.667	-.156	.652	-.027
Zscore(K)	-.808	.015	.476	.155
Zscore(Mn)	.407	.782	.115	.256
Zscore(P)	.732	.419	.243	.039
Zscore(Rb)	.290	-.627	.017	-.030
Zscore(S)	.858	-.212	.016	-.149
Zscore(Si)	-.880	-.098	.115	.290
Zscore(Sr)	-.154	.903	.184	-.106
Zscore(Ti)	-.849	-.222	.168	.120
Zscore(V)	.217	-.227	.778	.132
Zscore(Zn)	.017	.953	-.083	.136
Zscore(Zr)	.063	.090	-.255	.775

Appendix 4

Description of Proposed Works – Pitcarmick

The following appendix comprises the Description of Proposed Works at Pitcarmick early medieval longhouses. Excavation was planned for Spring 2020 and consent to excavate the scheduled monuments was granted in October 2019. However, government-enforced limitations as a result of the Covid-19 pandemic meant that this could no longer go ahead in the remaining project timeframe.

HES SMC Form - Description of Proposed Works

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This document outlines the proposed archaeological investigations for **Croft of Cultalonie, settlements, cairns and field systems** (SM5319)

Introduction

Whilst prevalent in Scottish identity, culture and tourism, the Picts remain one of the nation's least understood historical people (Noble et al. 2013a: 1136). Much of the academic discussion focuses on elucidating aspects of their visible monumental record, such as forts, power centres and the enigmatic symbols carved on standing stones across Scotland, and little attention has been paid to economic or social practices (Noble et al. 2013b; Hudson 2014: 110). Although this trend has been changing over the past decade – Alex Woolf, for example, has forced a re-evaluation of our understanding of the political organisation of Scotland during this time, and excavations of the high status site at Rhynie are adding to a growing corpus of knowledge regarding networks of trade and communication – there continues to be a considerable absence of knowledge regarding the daily lives of people within the Pictish Period (Woolf 2006: 182; Noble 2014). Whilst this is partly due to surviving documentary sources being limited in number and largely contentious, the primary issue lies in the fact that very few Pictish farmstead settlements have been subjected to thorough archaeological investigation.

Geoarchaeological techniques clarify site formation processes and are a powerful research tool for identifying floor deposits, distinguishing their composition and linking this to post-depositional events (Milek and Roberts 2013). Through an integrated programme of research, they offer a unique opportunity to gain detailed insights into the processes affecting a site before, during and after its occupation (Goldberg and Macphail 2006: 5). By first establishing a clear understanding of the depositional and post-depositional processes that have impacted occupation deposits, patterns of artefact, microrefuse and geochemical distribution can be interpreted in an attempt to understand the spatial organisation of activity areas (Milek and Roberts 2013: 1845). This is imperative to the study of settlement sites and past societies as a whole, as it offers insight into the type of economic and social activities being conducted at a site, the ways in which households and communities organised the practices which governed everyday life, and the living conditions experienced by the people who occupied and worked in these buildings (Goldberg and Macphail 2006: 216-219).

Perhaps more significantly, however, is the fact that this information can also be used to manage these sites. Using geoarchaeology to identify formation events permits an assessment of how sites are being impacted through processes such as bioturbation, leaching and erosion. Many of the known Pictish Period sites exist only as cropmarks or very shallow earthworks, and much of the information within them has already been lost or significantly altered. Lowland sites, for example, are generally truncated by ploughing, urban development or coastal erosion (e.g. Rhynie, Burghead, Dunnicaer), while those uncovered in upland areas seem to have no preserved floor deposits for reasons that are yet to be understood (e.g. Lair in Glenshee). As such, geoarchaeology has the potential to both elucidate aspects of daily life and meaningfully inform cultural heritage management solutions.

Yet, whilst these techniques have proved highly effective on Viking Age sites and ethnographic sites in Scotland and Iceland, there has been little to no geoarchaeological work conducted on Pictish Period buildings (Milek and Roberts 2013). This project therefore seeks to address this by applying geoarchaeological techniques to both new and previously excavated areas in order to achieve an understanding of the processes impacting these sites at various environmental settings across north east Scotland. Through a partnership with Durham University, University of Stirling and Historic Environment Scotland, these samples will form a body of work for a PhD titled *Geoarchaeological Approaches to Pictish Settlement Sites: Assessing Heritage at Risk.* Results will help guide conservation and management solutions whilst assessing the research potential of fragmentary buildings if analysed using geoarchaeological methods. Proposed outcomes include peer-reviewed articles, an assessment-of-risk report, and practical guidelines on how and when to take different types of geoarchaeological samples.

Site history

Pitcarmick North is a section of landscape situated on the west side of Strathardle, centred on NO 061 581. It consists of a number of cairns, round houses, long houses and rectangular houses set among field boundaries and clearance cairns. Work undertaken at Pitcarmick arose from the publication of the Royal Commission survey for North East Perth (1990), which mapped and identified a particular type of longhouse with rounded corners (now known in the literature as 'Pitcarmick houses') (Foster 2004: 56, Carver et al. 2012: 146). Following an initiative from the Department of Archaeology at Glasgow University, the area was investigated by John Barrett (of Glasgow, now University of Sheffield) and Jane Downes (of Sheffield, now UHI). Between 1993 and 1995, five areas containing low earthworks were partially excavated and subjected to topographic, phosphate and magnetometer surveys in an attempt to understand the buildings and place them within a multi-period landscape (Carver et al. 2012: 150).

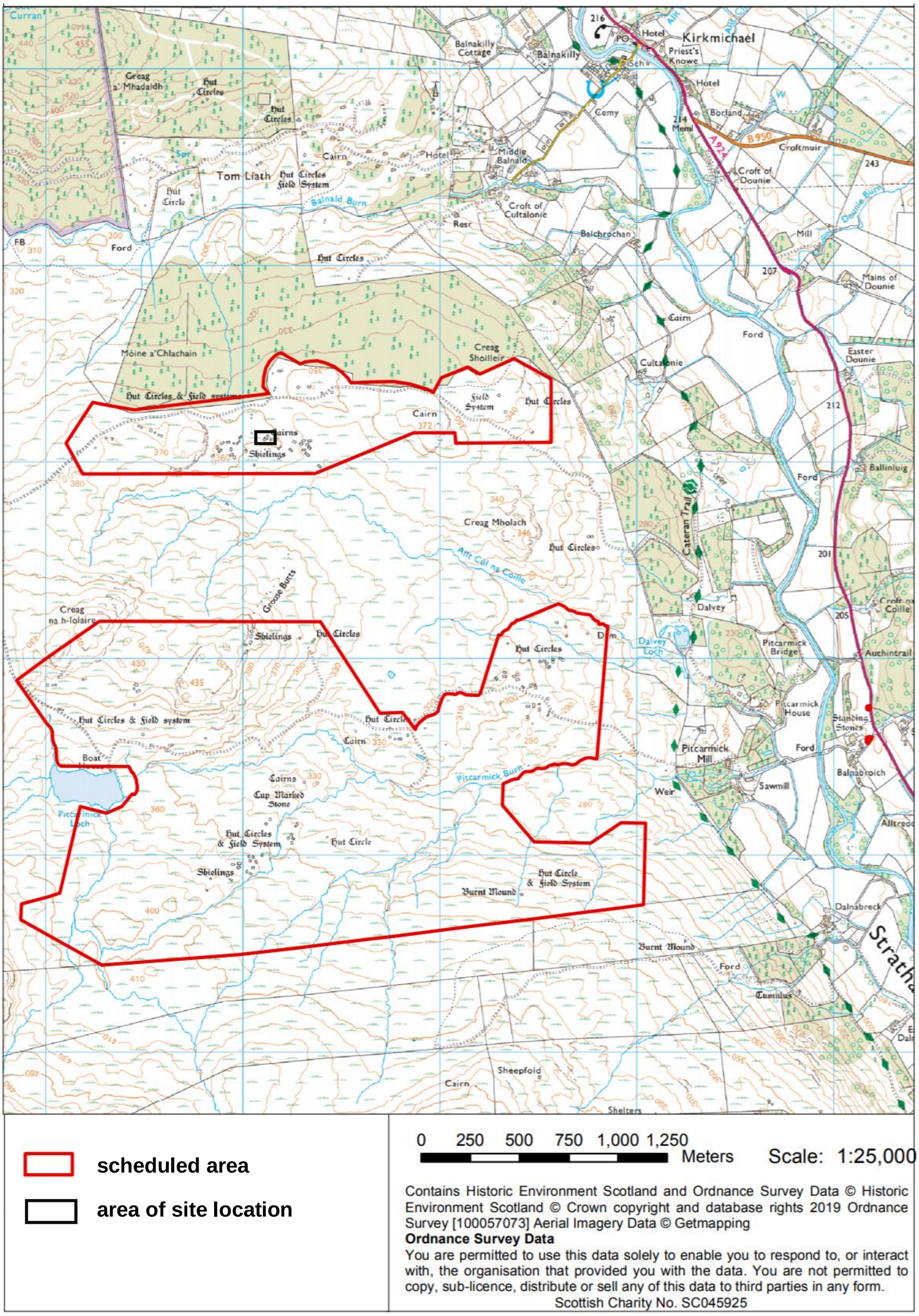

***Fig. 1**: Area of site location in relation to scheduled area*

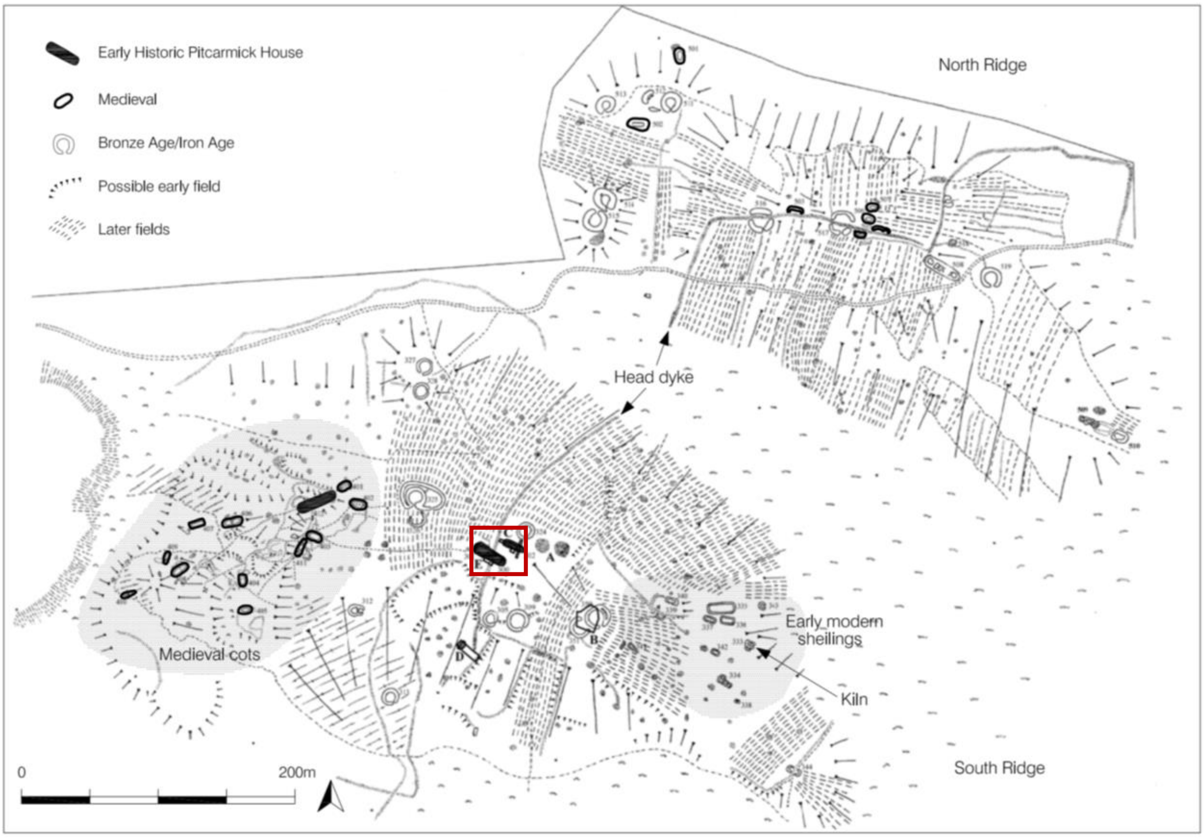

Fig. 2*: Plan of structures designated at Pitcarmick North (red box indicates study site – Area C + E)*

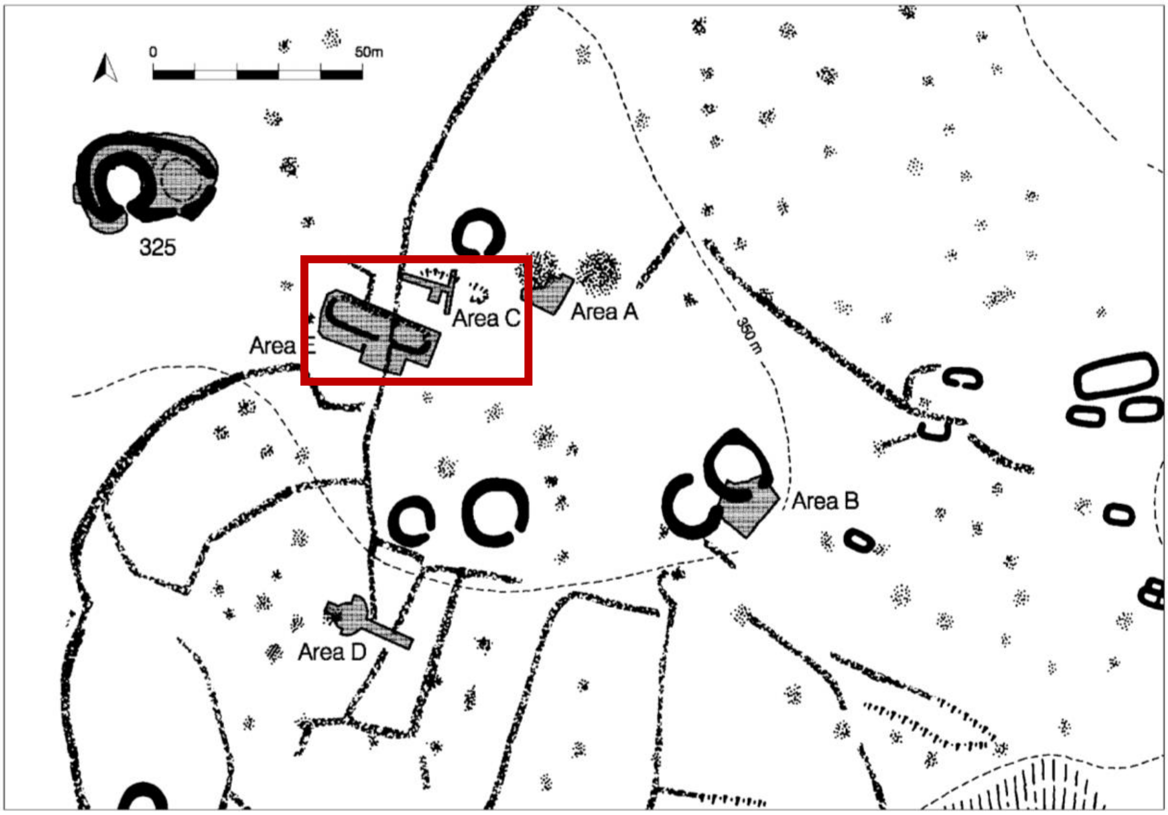

Fig. 3*: Targets of excavation A-E 1993-5 (Carver et al. 2012: 148)*

Overview of excavations (adapted from Carver n.d.):

- **Area A** (1993) was situated south of the more westerly of two large cairns (presumed to be burial cairns). Excavation sought to investigate contemporary and later activity within their vicinity.

- **Area B** (1993) was placed contiguous to two overlapping roundhouses, on their south-east side. A third roundhouse lay beneath them. The intention was to study the sequence of buildings (B1, B2 B3).

- **Area C** (1993) was a T-shaped trench placed over the south side of a Pitcarmick house (C1), and resulted in the excavation of less than half of it. Radiocarbon dates obtained show that C1 was in use in the Pictish period between 700 and 850 AD. Refashioning of the hearth and a later radiocarbon date of 1020-1180 AD indicated that the building had at least two periods of occupation. Area C identified evidence of ploughing and much of the wall material had been washed up to 3.8m downslope.

- **Area D** (1993/5) consisted of a section through a lynchet D2 (1993) and the excavation of a cairn D1 (1995) connected by a 20m trench.

- **Area E** (1994) was intended as the total excavation of a larger 'Pitcarmick-type' house and was the focus of the 1994 season. It resulted in the definition of a long Pictish building with hearth and drain (**E1**) and a small medieval building over its west end **(E2**). Area E identified a number of later cultivation marks on a N-S orientation; these cut both the north and south bank of the house. Ardmarks in the eastern sector of building E1 were sealed by a compact loamy silt, defined as an occupation level or trample which had filled the central drain.

Results of the campaign were subsequently published in two parts by Martin Carver – an article in *PSAS* entitled 'Pictish byre-houses at Pitcarmick and their landscape: investigations 1993-5' and an online archive. Little work has been conducted in the 25 years since these excavations, and it was identified that the approach taken limited structural and social interpretations (Carver 2012: 150).

Project summary

The work proposed here seeks to provide a comparative case study which will feed into the wider research aims of the aforementioned PhD project. Given their partial excavation, old excavation trenches will be opened in **Area C** and **Area E** (NGR: NO 0611 5811) in order to take micromorphology and sediment samples from floor deposits and and turf walls exposed in the sections. The programme of archaeological work is small in nature and targeted towards answering a number of key questions, namely:

- What are the site formation processes affecting Pictish Period dwellings?
- Are there observable changes in the preservation of buildings since their initial excavation c. 25 years ago?
- What is the most appropriate management strategy for earthwork structures in heather moorland?
- Is there evidence of relic floor layers in the exposed sections and what can they tell us about cultural and/or preservational processes?
- How does the information gathered compare with other Pictish settlement sites?

The samples collected will provide crucial data which can be used to understand site formation processes within a different environmental setting and inform heritage management solutions. In addition, photographs and section drawings produced as a result of the excavation will add to the online archive (in which there are currently no section drawings).

***Fig. 4**: Current state of Area C (left) and Area E (right) - (taken from SE during a site visit on 24/07/19)*

<u>Methodologies of the proposed work</u>

Excavation strategies

All areas will be subjected to a visual survey in order to assess whether evidence of the 1993-5 excavations is apparent. This will also be used to investigate any processes which may be impacting the sites at a local and landscape level (e.g. trampling, burrowing, erosion). The landowner has agreed to burn the heather during the burning season (March-April) – this will remove the surface vegetation and make visual survey and turf removal more manageable.

Diagrams produced during the initial 1993-5 excavations (**Fig. 5 and 6**) will be used to determine the approximate location of old excavation trenches/baulks. The areas will be carefully deturfed and all modern topsoil will be trowelled until the trenches become visible in plan. All deturfing, topsoil removal and excavation of trenches will be done by hand. All removed turfs will be kept aside for reinstatement. Section cleaning will be aim to remove as little material as possible and extend to a maximum of 3-4cm, depending on the level of disturbance.

Previous work at Pitcarmick has suggested that the top layer is composed of turf and relic ploughsoil which produces little information and is largely archaeologically sterile. Given that all targeted areas have previously been excavated, sediments encountered during topsoil removal will consist of backfill and no artefactual material is expected to be recovered.

Sampling strategy

The primary focus of the excavation is to retrieve micromorphological samples from intact archaeological deposits exposed in previously excavated sections. These will be taken using standard Kubiena tins (6cm x 5cm x 4cm), at staggered intervals down the section profile. A stretch of section will be exposed in order to produce detailed photographs and illustrations (currently missing from the online archive), and samples will be taken from the most appropriate part of the section. From each area of the structure, this is likely to include a series from an interior area (targeting relic floor layers) and a wall layer (targeting building material). Approximately 2cm of material will be removed on each edge of the Kubiena tins in order to successfully remove them from the section. This additional material will be collected and submitted for geochemical analysis where appropriate. This strategy ensures maximum information retrieval with minimal intervention.

As this work feeds directly into a geoarchaeology-based PhD, sample collection will primarily focus on retrieving information related to site formation processes and post-depositional changes. In order to ensure this work is achieved most effectively and with minimal intrusion, a number of protocols have been established:

- The site has been visited prior to excavation in order to assess access, preservation and trench location (this has been conducted alongside Sir Michael Nairn, the landowner of Pitcarmick Estate)
- During the excavations, a soil specialist (Dr Karen Milek) will advise on geoarchaeological approaches and ways to maximise information retrieval from the excavated deposits and soils

- Profiles exposed in the section edges will be carefully cleaned and recorded before/during sampling (hand and digitally planned at 1:10 and photographed)
- All samples will be recorded on section drawings and photographed accordingly
- Samples will be submitted for geoarchaeological analysis
- Environmental sampling (for soil flotation, geochemistry and micromorphology) will follow Historic England guidance (Historic England 2015)

Team and implementation of research design

The project is led by two site directors – Karen Milek (Department of Archaeology, Durham University) and Vanessa Reid (PhD student, Durham University). Both have experience of Scottish archaeology and of excavating Pictish Period structures. Karen Milek has extensive experience in geoarchaeology and of creating soil sampling programmes for the study of Pictish Period settlement sites. The team will also consist of a small number of volunteers from the Department of Archaeology at Durham University and the Perth and Kinross Heritage Trust.

Resources to carry out works

The excavation and post-excavation analysis have been funded through a NERC IAPETUS research grant as part of the associated PhD project. Historic Environment Scotland also contribute to the overall PhD research grant through a CASE partnership.

Post-excavation and publication strategy

Analysis of the samples will be undertaken by Vanessa Reid as part of her PhD research. This includes all geochemical and micromorphological analysis. Training in all aspects will supervised by Karen Milek and Paul Adderley (University of Stirling). Results of the research will feed into a number of publications produced through a PhD-by-publication format. These include peer-reviewed articles on the processes impacting Pictish settlement sites and a detailed Data Structure Report. Results of the analyses will also be used to inform a set of guidelines on the application of geoarchaeology in Scotland, produced in partnership with Historic Environment Scotland.

Proposed work and rationale

A programme of work is proposed at Pitcarmick Estate, in order to target key elements of the site that can provide information about the composition of floor and wall layers and their alteration. Trenching will focus exclusively on reopening small portions of previously excavated sections (**Fig. 3, 4**). This allows for the collection of samples in order to assess the preservation conditions on a previously excavated earthwork site. The overall excavation area makes use of previous trenches and covers a very small proportion of the site (c. 5% of each building).

<u>Area C – partially excavated during 1993-5 field seasons</u>

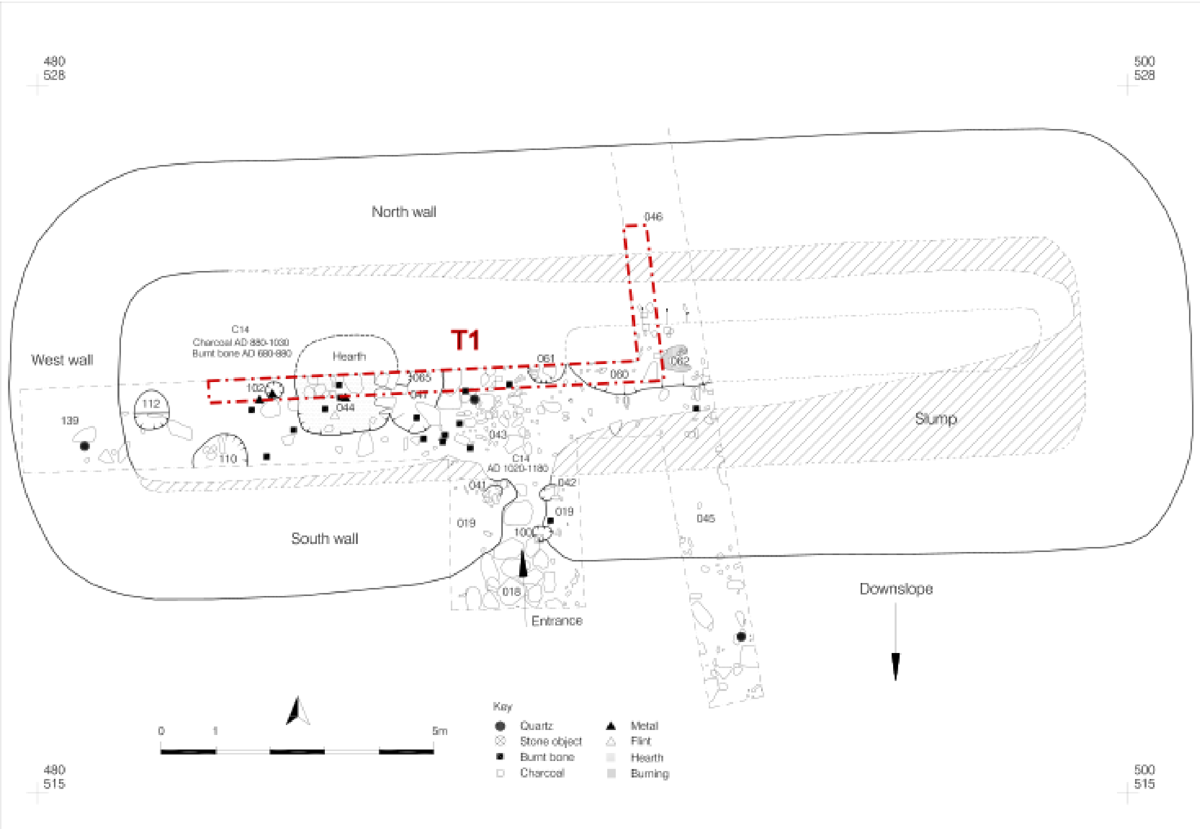

***Fig. 5**: Proposed trench location in Area C, Pictish Period house (adapted from Carver et al. 2012)*

Trench 1 – Area C

Trench 1 is an L-shaped trench designed to re-expose part of a south-facing interior section (including hearth) and part of an east-facing turf wall in Area C. The trench is 7m and 3m in length on the long-axes, and will extend 0.5m into the backfilled material in order to allow working access. This permits the collection of geoarchaeological samples from both interior and wall material, in order to assess the preservation across parts of the building and from different contexts. It also allows the hearth and other interior features to be recorded in section.

<u>Area E – fully excavated (excluding baulks) during 1993-5 field seasons</u>

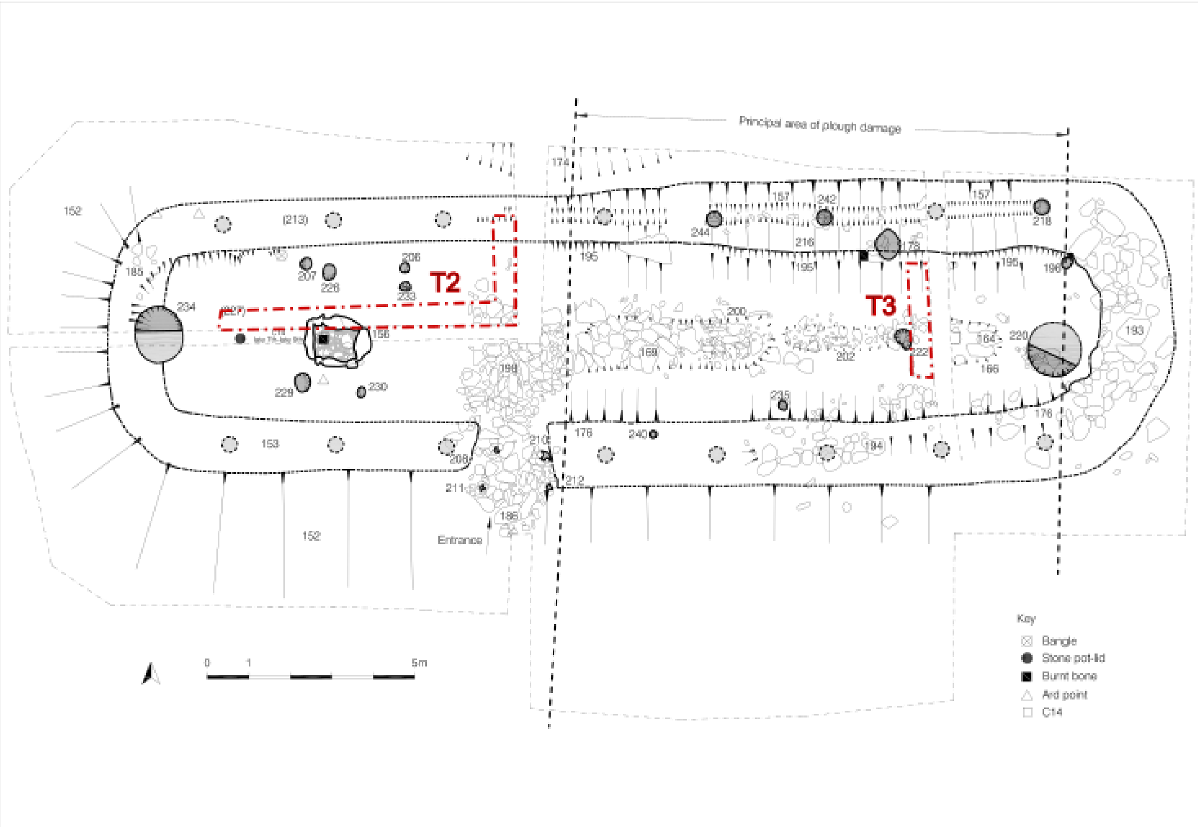

Fig. 6: *Proposed trench locations in Area E, Pictish Period level (adapted from Carver et al. 2012)*

Trench 2 – Area E

Trench 2 is an L-shaped trench designed to re-expose parts of north-facing and west-facing baulks in Area E. It follows a similar format to Trench 1, in that it is designed to allow sample collection from both interior and wall material, as well as recording these features in section. The trench is 6m and 3m on the long axes and will extend for 0.5m into previously excavated material. This will provide comparative data across both structures and permits an assessment of the impact of later medieval activity across the west end of the building.

Trench 3 – Area E

Trench 3 is a 3m linear trench designed to re-expose a west-facing baulk on the east end of Area E. This permits the collection of samples from a part of the building not impacted by medieval structural reworking. The east end of the building was recorded has having been the principal area of medieval plough damage, and collection from this baulk will allow a comparative assessment on the impact of this on preservation.

Justification for proposed work

1. The trenches proposed at Pitcarmick are designed to assess the preservation of floor and wall material in Pictish Period buildings. Samples collected as a result of the excavation will allow for a characterisation of the site formation processes impacting the sites and a comparison between both upland/lowland and rural/fortified settlements. Very few sites of this nature have been identified and all have poor preservation for reasons that have yet to be fully understood. Elucidating the processes which create these conditions will therefore positively influence site interpretations.

2. Samples collected will also be used to assess the impact of a heather moorland environment on overall site preservation. This will involve assessing the depth of root penetration, susceptibility to burrowing activity, degree of trampling and/or animal erosion, and the impact of burning seasons on geochemical signatures. This information will then be reviewed against possible management strategies and recommendations made. All information will be disseminated to the landowner and wider audiences.

3. Study of the Picts continues to focus heavily on high status sites or fortified settlements (e.g. Rhynie, Burghead) and there is a significant lack of research into rural settlement. Work conducted at Pitcarmick will help to address this issue and tie into several of the key research issues identified in the ScARF Medieval Panel Report (2012). This includes making use of scheduled sites to investigate medieval settlement and applying geoarchaeology to sites with little observable strata.

4. In accordance with HEP4, outlined in Historic Environment Scotland's Scheduled Monument Consent Policy (2019), the work proposed represents a minimal level of intervention. All areas of excavation make use of trenches previously opened between 1993-5 and there are no new areas selected for investigation. This approach will therefore answer a set of key research questions and add to an existing site archive, whilst representing no additional threat to the surviving archaeology.

5. The project will provide unique training opportunities for university students, researchers and local volunteers sourced through the Perth and Kinross Heritage Trust (PKHT). Geoarchaeological sampling is not often the focus of excavations in Scotland and this project provides an opportunity to share knowledge and practical skills with volunteers. Karen Milek has extensive experience in designing and conducting geoarchaeological sampling strategies, and training will be of a high quality.

Outputs and Stakeholder Engagement Outcomes

The results of this project will provide:

- Academic research outputs in the form of peer-reviewed journal articles and an associated PhD
- Popular outputs in the form of informal progress reports disseminated via Durham Archaeology's media platform and other social media outlets (e.g. HES blog, Twitter)
- An interim report sent to all relevant bodies including Pitcarmick Estate
- Updated archive material including section photographs and digitised drawings

- Material towards the production of Scottish geoarchaeological guidelines, produced in partnership with Historic Environment Scotland

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