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FACTORS AFFECTING THE SURVIVAL OF METAL PLOUGHSOIL ASSEMBLAGES

AN ASSESSMENT OF LEAD BULLETS FROM 17TH-CENTURY FIELDS OF CONFLICT

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Abstract

All archaeological buried assemblages are subject to deterioration. Research has focused on the decay of artefacts in stratified contexts from excavations, with less consideration given to the objects from the ploughsoil. In recent years, the acceleration of metal artefact decay has been witnessed, with increases in soil acidification, pollution and the intensification of agricultural practices being identified as key factors in this process. This project examines the various factors which contribute to the decay of metallic archaeological materials in topsoils. The study seeks to identify associations between the decay of materials and their burial environments in order to identify the principal factors influencing deterioration. This will assist in the prediction of site condition and enable the design of mitigation strategies to aid preservation and conservation, highlighting the importance of ploughsoil assemblages as a significant part of our cultural heritage.

This research explores the threats artefacts face in unstratified contexts by designing and applying a condition assessment and mapping the condition of artefacts across landscapes. 17th-century British Civil War sites of conflict, including both battlefields and siege sites, are used as case studies for this research, with lead bullets as the object type examined. Battlefields were chosen for study because they are particularly vulnerable to loss of data as the majority of evidence survives in the form of scatters of lead projectiles and other artefacts in the topsoil.

Three main parameters affect the survival of metal in the ground: soil chemistry and superficial geology, the historic land use of sites, and the chemical composition of artefacts. These factors have been addressed in turn for each case study, in an attempt to identify which parameter has the most impact on the condition and preservation state of lead bullets.

This study has revealed the condition of artefacts can vary greatly in ploughsoil environments. Analysis has shown that a soil's pH and texture have a significant effect on the preservation of lead bullets. Tin content of the bullets has a slightly negative impact on their preservation. An important discovery has been that probably the most significant aspect of the burial environment is land use history. Bullets were in consistently better condition in permanent pasture fields, overriding the significance of soil chemical attributes, revealing the impact arable farming has had on the preservation of buried metallic artefacts. It appears the most effective conservation strategy in future would be to retain land under pasture or convert arable land to pasture in order to preserve buried assemblages for the long term.

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Glossary

Acidification- the process of becoming acidic
Acrylonitrile Butadiene Styrene (ABS)- a thermoplastic polymer used in engineering
Aeolian- relating to the action of wind
Agri-environment scheme- schemes providing funding to farmers and land managers to farm in such a way that supports biodiversity
Alluvial- deposit of soil left by flowing floodwater
Anaerobic- the absence of air
Anion- a negatively charged ion
Anodic- a positively charged electrode
Anoxic- total depletion in the level of oxygen present
Bioturbation- the disturbance of sedimentary deposits by living organisms
Bronze disease- a form of severe deterioration in copper-alloys caused by copper chloride reacting in air to form bulky, loose pale green crystals
Carbonation- involves the binding of carbon dioxide to substrates
Cation Exchange Capacity- the total capacity of a soil to hold exchangeable cations
Cation- a positively charged ion
Colloid- a mixture in which one substance of insoluble particles is suspended throughout another substance
Colluvial- sediments that have been deposited at the base of hill slopes by continuous down slope creep
Compton scattering- the scattering of a photon by a charged particle, resulting in a decrease in energy
Correlation coefficient- to quantify a correlation and dependence meaning between two or more values in statistics
Crystallographic- referring to the arrangement of atoms in a material
Deionised- water that has had the ions removed
Denitrification- where nitrate is reduced and ultimately produces molecular nitrogen
Diagenesis- the post depositional interaction between the burial environment and archaeological evidence
Dip wells- tubes drilled vertically into the ground which fill with water and are measured for environmental monitoring purposes
Diffraction- Occurs when a wave encounters an obstacle resulting in the bending of light
Dispersant- a liquid or gas used to disperse small particles in a medium
Erosion- the action of processes (water flow/wind) that break down and remove soil and rock sediment and then transport it to another location

Eutectic- a mixture of substances that has a melting point lower than any of the pure component substances

Flocculation- the process by which a substance forms into small clumps

Fluorescence- emission of light by a substance that has absorbed light

Friability- tendency for a substance to crumble or break

Galvanic corrosion- where one metal corrodes more rapidly when it is in electrical contact with another metal

Gleys- waterlogged soil lacking in oxygen, typically grey or blue in colour

Humic- humus referring to the major organic constituents of soil

Hydroxyl- hydroxyl groups contain oxygen bonded to hydrogen (OH^-)

Illite- a clay mineral with a structure which does not expand on absorption of water

Ion- a particle with an electrical charge

Isomorphous substitution- replacing one atom by another atom of similar size, without changing the structure of the mineral (e.g. exchange of cations in clay fraction with cation near surface of clay)

Isotope- atom of an element with the same number of protons and electrons but a different number of neutrons, resulting in a different mass

Kaolinite- the most common clay mineral

Laser diffractometry- measures particle size distributions by measuring the angular variation of light scattered as a laser beam passes through a dispersed sample

Lithic- stone tool

Micelle- particle of colloidal dimensions

Microbial- relating to or characteristic of a microorganism

Milling- grinding of a substance in a mill with a rotating tool

Mouldboard- a board in a plough that turns the earth over

Montmorillonite- a common clay mineral that form when they precipitate from water solutions

Morphology- the study of the form and structure of an organism or object

Nighthawking- British term referring to the theft of archaeological artefacts from protected archaeological sites under cover of darkness

Numismatist- a person specialising in the study of coinage

Octahedral- molecule with six atoms arranged around a central atom, comprising eight faces

Original surface- the surface of an artefact at the time of its abandonment, before post depositional effects

Oxidation- when a substance loses electrons

Passivation- when a metal forms solid corrosion products on its surface preventing or restricting the underlying metal from further attack

Patina/patination- a film on the surface of an object produced by oxidation and exposure over a period of time

Peds- aggregation/binding of soil particles in a clump

Piezometer- measures liquid pressure in a system, used for monitoring groundwater levels

Podzols- group of soils dominated by acid parent material

Potentiometric titration- a volumetric method in which the potential between two electrodes is measured as a function of the added agent

Redox potential- a measurement of the tendency of a chemical species to acquire electrons and thereby be reduced

Refractive index- measures the change in speed of light as it passes from a vacuum into a material

Sedimentation- the process of settling or being deposited as sediment

Taphonomic- the study of post depositional processes on an object (decomposition, burial, preservation)

Tetrahedral- a molecule with a central atom with four atoms surrounding it forming four faces

Ultrasonication- the application of ultrasonic waves to a solution or material resulting in agitation

Unstratified- not in distinct layers

Vitrification- the transformation of a substance into glass. In clays intense heat fuses particles together making the clay body impervious to water

Abbreviations

AOD- Above Ordnance Datum

CAP- Common Agricultural Policy

CEC- Cation Exchange Capacity

COSMIC- Conservation of Scheduled Monuments in Cultivation

Defra- Department of Environment, Food and Rural Affairs

EEC- European Economic Community

EU- European Union

Eh- Redox potential

GPS- Global Positioning System

HER- Historic Environment Record

LIDAR- Light Detection and Ranging

NPPF- National Planning Policy Framework

OM- organic matter

PAS- Portable Antiquities Scheme
Rpm- revolutions per minute
XRF- X-ray Fluorescence
RH- Relative Humidity
XRD- X-ray Diffraction
UKSO- UK Soil Observatory
USDA- United States Department of Agriculture

#English Heritage (EH) was split into Historic England (HE) (government service) and the English Heritage Trust (charity) on 1st April 2015. Throughout this thesis all research carried out prior to April 2015 will be referred to as English Heritage and work produced after this date will be referred to as Historic England.

#Unless stated otherwise, all photographs in this thesis were taken by the author.

Chemical formulae

Chemical compounds and their formula mentioned in this text:

Compound	Chemical	Formula
Anglesite	Lead sulphate	$PbSO_4$
Berndtite	Tin sulphide	SnS_2
Calcium chloride	Calcium and chloride	$CaCl_2$
Cassiterite	Tin oxide	SnO_2
Cerussite	Lead carbonate	$PbCO_3$
Chloropyromorphite	Lead phosphate chloride	$Pb_5(PO_4)_3Cl$
Cotunnite	Lead chloride	$PbCl_2$
Galena	Lead sulphide	PbS
Herzenbergite	Tin sulphide	SnS
Hydrocerussite	Lead carbonate	$Pb_3(CO_3)_2(OH)_2$
Laurionite	Lead chloride	$Pb(OH)Cl$
Lead	Metallic lead	Pb
Litharge	Lead oxide	PbO
Massicot	Lead oxide	PbO
Phosgenite	Lead carbonate chloride	$PbCl_2CO_3$
Plumbonacrite	Lead carbonate hydroxide oxide	$Pb_5O(CO_3)_3(OH)_2$

1 Introduction

Archaeological materials are under a constant threat of decay. Both in the field and in museum stores conservation and preservation of archaeological assets is a continuing battle. In recent years studies have shown that the deterioration of materials poses a great threat to the buried archaeological resource of England, particularly within the ploughzone (Oxford Archaeology and Cranfield University 2010; Foard, Janaway, and Wilson 2010; Humble and Holyoak 2014). Research has focused on the preservation of organic materials due to their rare survival in archaeological contexts, but it has been highlighted that there is an increasing threat to the preservation of buried metal objects. The decline in the condition of materials restricts the amount of reliable data which can be obtained from artefacts. Ongoing deterioration puts into question the effectiveness of current heritage and conservation management policies on sites with significant metal assemblages in the ploughzone.

1.1 Scope of study

This project focuses on identifying the main threats towards buried metal assemblages in ploughsoils, assessing the impact these factors have on the archaeological resource. The main threats towards buried metals comprise three categories; the soil chemistry and superficial geology of a site, the historic land use of a site, and the chemical composition of the object. All of these characteristics will play a part in preserving or degrading a buried metal resource. The *ploughsoil* or *topsoil* usually refers to the upper 0.20-0.30m of the soil column that has been disturbed by agricultural activity, and is known to be under great threat from chemical and mechanical damage, decay and data loss in Britain and Europe. There have been few attempts at quantifying the threat to loss of data from ploughzones in England, which this project seeks to rectify.

The assets at greatest risk of deterioration in the archaeological record are those still buried in the ground and it is here that the greatest potential for action exists. Current policy on portable antiquities outlined by Historic England, including artefacts in ploughsoils, state that investigation through acts such as metal detecting should be restricted or controlled on sites that have been legally designated in order to protect assemblages for the future. Historic England also state that changes may be required to cultivation regimes where research demonstrates that *in situ* remains are being damaged by industrial or agricultural processes (Historic England 2018). In 1992 the Valletta Treaty outlined the importance of protecting, preserving, and the scientific research of archaeological heritage in Europe, opting for preservation of archaeological sites *in situ* where possible (Dobinson and Denison 1995; Huisman 2009). An avenue of research is dedicated to preservation *in situ* as opposed to rescue attempts by extracting material from their burial environment. It is often assumed that artefacts are more stable left in their natural burial environment and can be conserved in the ground for future generations (Nixon 2004; Corfield *et al.* 1996; Corfield 2004). However, preservation *in situ* all depends on the given environment and is often impractical, particularly in constantly changing environments such as ploughsoils.

It is sometimes thought that recovering artefacts from ploughsoils is the only way to protect the artefacts in the long term. However, other ways of preserving artefacts in the topsoil need to be explored, such as identifying vulnerable sites, addressing the land use and altering agricultural regimes (Historic England 2017, 36). Further research is required to assess whether *in situ* preservation is a viable conservation strategy in the ploughzone.

Work carried out by English Heritage and the University of Bradford highlighted a serious lack of understanding in the condition of metal artefacts in the ploughsoil, which led to the instigation of this current study (Foard, Janaway, and Wilson 2010; English Heritage and University of Huddersfield 2014; Historic England 2017, 29). They identified a number of requirements in order to better understand the decay process of metal artefacts in the ploughzone. These requirements included:

- The development of a standard measure of condition for artefacts in the ploughsoil in order to compare assemblages

- Data presenting correlations between environmental conditions and artefact conditions

- New systematic sampling on a number of sites

- Greater understanding of the effects of agriculture on the condition of artefacts in the ploughsoil

- A framework to assess risk to various types of site

- Ways to minimise decay on sites by alteration in cultivation methods

They identified a need to develop a condition ranking system in order to assess the condition of assemblages in the ploughzone; to establish ongoing rates of decay, to rank the importance of remaining evidence in the ground, and define measures to minimise future loss of assemblages on British sites. Dobinson and Denison (1995) also suggested that mapping the condition of metal artefacts in ploughsoils in different parts of England is also needed to reveal differences in preservation. English Heritage deemed it crucial to improve our understanding of the relative importance of key environmental factors in the decay process, the effect of modern agriculture on the condition of metal artefacts in the ploughzones, and the data loss resulting from this decay. Only then can steps be taken to improve the heritage management of sites with assemblages residing in the ploughzone. If the condition of materials can be understood and their decay trajectory predicted, future research and conservation can be prioritised to those sites under greatest threat of damage or loss.

1.2 This project

This project was instigated from the gaps in knowledge identified above, so that a greater understanding of ploughzone archaeology will help to reduce cultivation impact on sites and to identify sites at serious risk of data loss. This research will help to develop future mitigation strategies in conservation and land management for ploughzone archaeology.

It is important to address the threats buried assemblages face and which factors have the greatest impact on artefact preservation. Three main areas have an impact on the preservation of metal in the ground:

-Soil environment and superficial geology

-Land use (current and historic)

-Composition of objects

17th-century battlefields have been chosen as the site type for this study as the majority of their primary evidence exists as metal artefact scatters in topsoil deposits. They also contain large numbers of battle-related artefacts that have resided in the ploughsoil since deposition at the time of conflict. Therefore, artefact condition can be assessed based on their permanent presence in the topsoil, unlike most other site types where objects are progressively introduced into the topsoil from stratified contexts. Sites have been chosen which represent a range of geologies, soil types and land use histories in order to compare the impact these factors have had on the preservation of assemblages. In future it may be possible to predict the preservation of material in the ground using desk based assessments without the need for extended intrusive fieldwork. Lead bullets have been chosen as the object type for study as they are a ubiquitous object type from 17th-century battlefields, are plentiful in collections, can be dated almost to the exact day they entered the soil, and are highly standardised in their design, manufacture and use..

The majority of research on ploughzones has focused on lithics and ceramics, with a lack of research in metal finds, particularly those made of lead (Haldenby and Richards 2010, 1159-1160). However, researchers have noted a huge range of preservation of lead bullets from battlefields in England, ranging from poor to excellent, indicating that their condition and the reasons behind their state of preservation needs further investigation (Foard 2012, 119).

This study has developed a systematic condition assessment which can be applied to collections of lead bullets in order to compare their preservation within assemblages and between sites. Each of the factors highlighted above which affect preservation has been assessed for sites in this project, in order to establish as far as practicable the history of an assemblage's time in the ground. The environmental conditions on each site have been correlated with the condition of artefacts on three 17th- century sites of conflict, to establish the threats assemblages face from particular parameters, and to assess the relative impact each parameter has on the preservation of metal artefacts.

Initial project designs in the current research sought to study additional site types and metal types including lead, copper and iron in order to address the preservation of a range of metals. Preliminary research was conducted on Roman copper alloy coins from the sites of Alveston in Gloucestershire, and Rendlesham in Suffolk, in the hope that around 10 case studies would be studied in total. However, the process of developing condition assessments for further object types which had resided in the ploughzone for an unknown length of time made the project too broad and lacked detail on each site within the project timescale. The study began to lack depth and by focusing on three landscapes of one site type and one artefact type, a detailed history and in depth knowledge of the assemblages and battlefields in question could be established. The methodology can then provide a foundation on which to build and apply to other landscapes and assemblages where additional complexities need to be addressed in future across Britain and Europe.

By systematically recording the condition of assemblages and correlating this data with the land use history, superficial geology and soil type of the landscape in which they reside, steps can be taken to predict the likely deterioration of archaeological resources in given environments. Assessing multiple factors will help to address the relevant impact each factor has on the state of preservation of buried artefacts. This will further help to identify landscapes of good or poor preservation and mitigation strategies can be developed to aid future management and conservation of buried materials in the ploughzone. Only by fully evaluating the burial environment can we begin to understand the condition of buried assemblages and the significance, research and conservation potential of sites.

In future, the condition of materials can be predicted and heritage management can focus on retaining well preserved materials in their environment by restricting land use change. Steps can also be taken to reduce the impact certain factors have on the preservation of materials by modifying land use where necessary in order to conserve the archaeology of the ploughzone. The order of assessments carried out in this study is summarised in figure 1:

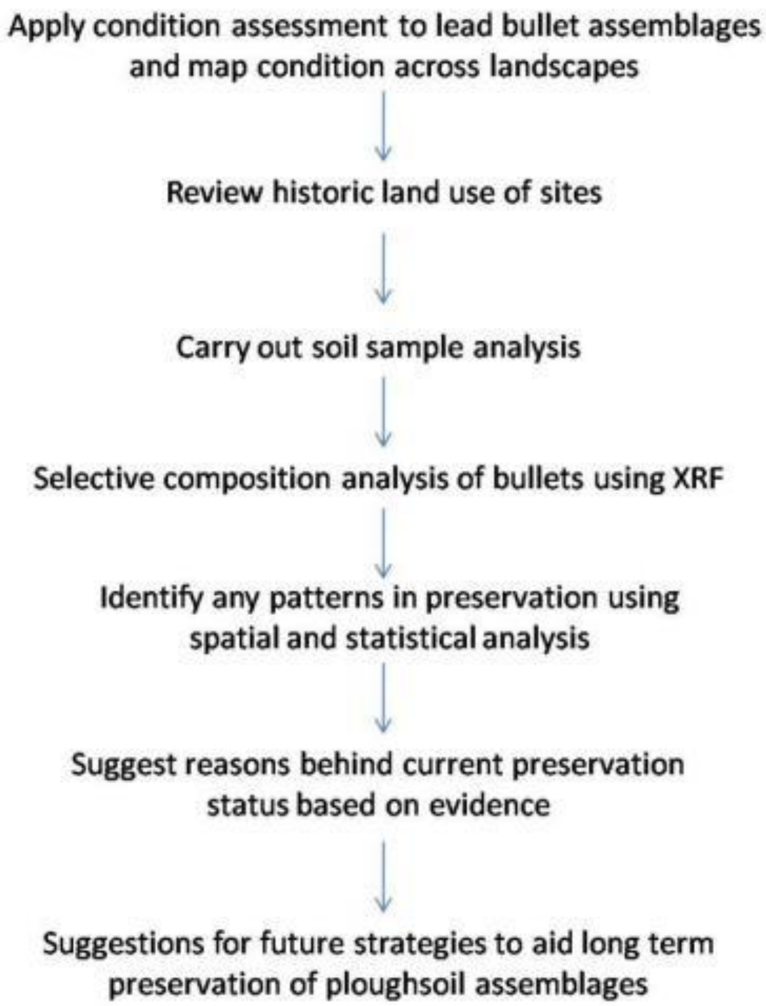


Figure 1: Order of assessments carried out in this study.

1.3 Project aims and objectives

The aims of this project are to identify and improve knowledge on the main threats towards the survival of buried metal assemblages in ploughsoils. Also, to assess the impact individual parameters have on the preservation of lead objects and to assess the condition of lead bullets in a measurable and standardised way. It is intended that the knowledge gathered through this project will provide essential data for the development of strategies for the long term management of sites with metal ploughsoil assemblages.

The objectives of this project are to:

-Develop an artefact condition assessment methodology that can be applied systematically to artefact assemblages to establish their general state of preservation

-Establish a fieldwork methodology for studying sites and collecting samples appropriate for burial environmental analysis from ploughsoil deposits

-Map the condition of lead artefacts in the ploughsoil across sites in order to identify any patterns in preservation

-Examine whether the metal composition (lead content and metal impurities) of bullets has an impact on the preservation of materials in the ground

-Address which factors have the most significant impact on the preservation or deterioration of lead artefacts in the ground by correlating environmental conditions with artefact conditions, with the application of statistical analysis

-Propose future mitigation strategies to manage, conserve and preserve ploughsoil assemblages for future generations

1.4 Thesis structure

Chapter 2 reviews previous research into the decay of metals in soils and addresses the main factors influencing the decay of metals. It discusses the ploughzone as an environment and the effects agriculture has had on the buried archaeological resource. It also explores the nature of soils and establishes a working hypothesis on aggressive vs. non-aggressive burial environments.

Chapter 3 outlines the selections of case studies and bullet assemblages and outlines the theory of lead corrosion. It reviews artefact condition assessments and establishes the condition assessment methodology applied in this study.

Chapter 4 outlines all desk based, field and laboratory methodologies used throughout this study, including landscape assessment, soil sampling strategies and laboratory techniques.

Chapters 5 to 7 present all collected data from three sites of conflict chosen for study (Moreton Corbet, Edgehill, Wareham). They assess the condition of artefacts and correlate this with their burial environments, using spatial and statistical analysis.

Chapter 8 presents cross site comparisons and overviews the results from all three case studies, drawing conclusions on the data.

Chapter 9 concludes, summaries the main findings of the research project, and presents recommendations for future work.

2 The burial environment

2.1 Previous work on the corrosion of metals in soils

The soil chemistry and superficial geology of a site can have great implications on the survivability of buried materials. In the 1930s scientists were aware of the damage chemical actions cause to soils themselves, by processes such as erosion and hydration (Beaumont 1938, 347), but it is not until more recently that the effects soil conditions have on metallic artefacts contained within them has been addressed. The relationship between the decay of metals and their soil environments has been a longstanding problem for engineering and economics. In 1956 it was estimated the cost of underground pipeline maintenance in the UK was approximately £20 million annually (Booth *et al.* 1967, 104). As a result, research into metal corrosion has focused on underground metallic structures to establish the aggressiveness of soils before structures are buried in the ground (Cole and Marney 2012).

One of the most extensive early studies into metal pipe corrosion was conducted by Romanoff (1962) who studied the corrosion of steel pilings exposed to soils for up to 40 years, correlating the corrosion of steel to soil attributes including resistivity, pH and soil type. Booth *et al.* (1967) went further, highlighting the significance of understanding the aggressiveness of a soil before metallic structures are buried in order to ascertain potential future corrosion issues, realising that no single comprehensive test will completely characterise a soil. This was one of the first attempts to adopt a scheme of testing soil corrosivity, keeping the number of tests to a minimum to indicate aggressiveness of a soil to aid engineers. The aggressiveness of soil from 87 sites was studied, recording the resistivity, redox potential (potential to be oxidised or reduced), water content, sulphate content, hydrogen uptake and pH of the soil samples. It was concluded that the aggressiveness of a soil can be ascertained from the redox potential and resistivity, referring to the water content; water contents >20% were deemed aggressive (Booth, Cooper, and Cooper 1967, 112).

Corcoran *et al.* (1977) applied soil aggressiveness methods to test the potential corrosivity of four soils where pipelines were buried in order to estimate the performance and life of new pipelines and to anticipate the failure of existing pipes. This work built upon Booth *et al.'s* work by allocating a scoring system to the soil corrosivity attributes; a soil that scores ten or above should be deemed aggressive (table 1).

Soil property	Range	Points
Resistivity (ohm/cm)	<700	10
	700-1000	8
	1000-1200	5
	1200-1500	2
	1500-2000	1
	>2000	0
pH	0-2	5
	2-4	3
	4-8.5	0
	>8.5	3
Redox potential (mV)	>100	0
	50-100	3.5
	0-50	4
	Negative	5
Sulphates	Positive	3.5
	Trace	2
	Negative	0
Moisture	Poor drainage, continuously wet	2
	Fair drainage, generally moist	1
	Good drainage, generally dry	0

Table 1: Soil test evaluation for corrosivity devised by Corcoran *et al.* (1977). A total of ten points or above indicates that the soil is likely to be corrosive to ferrous pipe.

Gilbert (1946) assessed the aggressiveness of soil based on soil type. He buried samples of copper, lead and lead alloy pipes in different British soils for up to ten years and examined the corrosion after one, five and ten years, assessing the corrosion visually over these time periods. He concluded that clay and peat soils were by far the most aggressive soils, with sulphate-reducing bacteria playing a significant role in corrosion. Gilbert rated the types of soil from most aggressive to least aggressive as follows:

Moist acid clay - wet acid peat - artificial ground - moist normal clay - chalk - dry acid sand

Jones (1996) also states that soils which are poorly drained and fine textured, such as clays, are likely to have higher levels of corrosivity (Jones 1996, 386). However, work by Tylecote (1979), who studied the corrosion of buried prehistoric bronzes, concluded that peats were quite preserving environments and sands and gravels were poor preserving environments, suggesting that sands and gravels have a damaging impact on the metal over a prolonged burial period. Kibblewhite *et al.* (2015) more recently state that preservation of metals is worst in free draining soils in oxygenated environments, whereas fine textured waterlogged clays are more preserving.

A disagreement exists as to which soil types promote the preservation of buried metals. Gilbert's corrosivity assessment focused on soil type rather than several chemical properties of soil over a period of several years, whereas Tylecote's assessment was on buried Bronze Age metal residing in soil for over 3,000 years. This may indicate that over prolonged burial periods, sands have a more damaging impact on the metal. Furthermore, Gilbert ranks *acidic* clay as the worst preserving environment, highlighting the importance of more than one factor in the decay process of metal. These studies also did not consider the land use history of sites or the effect of cultivation. A key factor is also the abrasive properties of the soil which results in the chemical breakdown of metals. Cultivation of soils has an impact on the level of abrasion taking place in soil, and it is important to address farming activities alongside soil texture to establish the potential impact on buried metal artefacts.

Establishing soil corrosivity has continued to be addressed in more recent studies (Adams 1994; Wilson 2004). Wilson based her assessment of soil corrosivity loosely around Corcoran *et al.*'s design and British Standard guidance (2003), measuring soil pH, soil type, soil moisture, conductivity, sulphate content and the presence of fertilisers, applying a scoring system to establish corrosivity (table 2) (Wilson 2004; British Standard 2003). She established that most commonly, the higher the moisture content, conductivity and level of fertilisers, the more corrosive a soil will be. She applied Gilbert's assessment of moist acid clays as being the most corrosive environment. However, she ranks clay as mid-range in terms of preservation which suggests it is the combination of moisture levels as well as the acidity of the clay which will make it a particularly aggressive environment.

Bertil *et al.* (2012) furthermore state that a number of field observations must be carried out in order to assess burial environments. This includes the soil type, superficial geology, organic matter present, the thickness of agricultural layers, groundwater table, soil moisture and texture. They suggest that burial environments can be evaluated purely on observations to save time and money on laboratory research. However, as research has shown, it is the chemical nature of the soil and not just the physical aspects which create an aggressive or non-aggressive environment for the preservation of materials, and so chemical analysis is required to fully evaluate the nature of the burial environment.

Parameter	Range	Score	Parameter	Range	Score
Soil solution pH	0-2 2-4.5 4.5-6.5 6.5-7.5 7.5-8.5 >8.5	5 3 0 0 0 3	Conductivity (μS)	<50 50-100 100-200 200-400 400-500 >500	0 1 2 3 4 5
Soil moisture	0-10 10-20 20-30 30-40 40-50 >50	0 1 2 3 4 5	Sulphate content	Positive Trace Negative	4 2 0
Soil type	Moist acid clay Wet acid peat Moist neutral Clay Chalk Dry acid sand Slightly acid sand	5 4 3 2 1 0 0	Presence of fertilisers	No fertiliser Fertiliser	0 2

Table 2: Scoring system for corrosivity levels of soils (Wilson 2004, 108).

Davidson and Wilson (2006) highlight the most significant threats to archaeological remains in soils are erosion and plough damage, changes in moisture content, changes in pH, and changes in organic matter (Davidson and Wilson 2006, 17). Ploughing changes the chemical balance of soils by altering the soil structure, allowing greater flow of air and water through soil pores. It also increases the rate of abrasion as soil particles become mobile and brush against each other and other substances within the soil. Davidson and Wilson highlight 'change' in several soil attributes as the key to damaging cultural heritage. If levels of water, oxygen, organic matter, conductivity and pH fluctuate then this leads to a potentially aggressive soil environment. This is particularly relevant when considering an environment which is in a constant state of change such as the ploughzone.

Recent studies have attempted to examine metal archaeological objects directly with their burial environments in order to ascertain any correlations between their state of preservation and the soil environment. Many have witnessed an accelerated deterioration in buried metals in the last 50-100 years. Madsen *et al.* review the preservation of prehistoric bronze artefacts from Denmark and reveal that more recently excavated artefacts are in much worse condition than artefacts excavated decades earlier (Madsen, Anderson, and Anderson 2004, 57). Fjaestad *et al.* (1998) asked "Are recently excavated bronze artefacts more deteriorated than earlier finds?" They studied 1600 bronze objects from Sweden in museum collections, estimating deterioration by weight and visual inspection of the artefacts. They concluded that modern contaminants such as pollution and acidification have accelerated corrosion rates and soil types that inhibit water and oxygen content including peats and clays are the most preserving environments, whereas sands and arable sites are poor preserving areas.

Gerwin and Baumhauer (2000) studied the correlation between iron artefacts and soil properties from five sites in Germany, taking samples from the soil matrix surrounding the artefacts. They concluded that the most important aspects of the soil affecting decay are the soil texture, soil acidity, the amount of soluble salts present, and drainage. They also state that recently noted increases in damage to buried metals could be due to higher levels of sulphuric and nitric deposits, soil acidification, and higher salt contents in agricultural soils from artificial fertilisers (Gerwin and Baumhauer 2000, 64). Chlorides and sulphates usually promote corrosion, but in their study levels of the anions (negatively charged ions) were too low to find any correlations. They suggested salt loads from road salts and fertilisers containing chlorides should be restricted. They concluded that sandy, acidic and well drained soils are the worst burial environments for preserving iron, which contradicts Gilbert's findings for bronzes and lead where clays were deemed the worst environments.

Nord *et al.* (2005) studied the composition of bronze and copper alloys and their corrosion products in order to determine the main factors causing their deterioration. They concluded that acidic soils, sulphur pollutants, the presence of soluble salts and increased aeration would accelerate corrosion of the metals. They also noted that objects that were once in stable conditions are now shown to be corroding at an accelerated rate due to acidification and salt pollution (Nord, Mattsson, and Troneer 2005, 314).

Neff *et al*. (2005) studied the corrosion of 40 archaeological iron objects from five sites in order to classify the corrosion formed in varying environments and found that the burial environments rather than the metal composition of the artefacts is more influential to the corrosion products which form on the surface of objects, with the diffusion of oxygen in the system having a great impact on the corrosion process.

One main cause in alteration to soil chemistry in the last half century is the use of agrochemicals on farmland and archaeologists have begun to question what effect this may be having on buried metal objects. Nord *et al.* demonstrated that once the chemical composition of the soil matrix is altered, the rate of corrosion can accelerate drastically (Nord, Mattsson, and Troneer 2005, 314). This has huge implications for the future preservation of buried artefacts and potential land management procedures. For instance, high salt content in soils from the use of artificial fertilisers has led to an increase in artefact damage (Scharff and Gerwin 1996), and the presence of various oxides, carbonates and sulphates in soils can have drastic effects on metal condition (Cronyn 1990, 171).

Other research has focused on the direct effect changing soil conditions can have on the condition of metals. The Fiskerton conservation management programme carried out field experiments in order to assess the effects raising water tables have on the preservation of buried materials. A range of materials were buried at the site including iron and copper coupons at a depth of up to 1.7m. Artefacts with greater levels of corrosion were found in the upper soil levels where oxides had formed on copper and iron samples causing rusting and damage, whilst deeper deposits resulted in protective sulphides forming on artefacts in an anoxic environment. Importantly, it was noted that in regions where the water table had fluctuated, changes in the water content had caused instability and the drying and re-wetting of samples caused protective corrosion products to detach from objects, leaving them in a fragmented state (Graham and Williams 2008; Historic England 2016a).

A further study was conducted by the Forestry Commission and English Heritage to study how land use and soil conditions affect the preservation of archaeological remains *in situ* in woodlands. Various materials were buried and burial environments monitored for water levels, redox potential, soil moisture and pH (Graham *et al*. 2007). Results showed that metal coupons buried in the topsoil formed bulky corrosion deposits and showed signs of pitting corrosion, whereas lower samples had dull grey surfaces, corresponding with the formation of corrosion in oxygenated and anoxic environments. They also note that any attempt at preserving archaeological remains *in situ* is impossible in an environment which is in a constant state of change, though they state studies in how land use affects preservation of materials should be extended to more forestry sites and other land use types in future (Graham *et al*. 2007, 1). These studies have revealed how damaging topsoils can be to the condition and long term preservation of buried metals.

2.1.1 Corrosion of lead in soils

The majority of research into metal decay in soils has focused on copper and iron artefacts, with a noticeable lack of research into the decay of lead antiquities. Lead is often deemed of less archaeological 'value' than other metals and is believed to be more durable than other metals in the ground (Stos-Gale 1985, 3; Kibblewhite, Toth, and Hermann 2015). However, lead can be sensitive to damage and can become brittle over time. Continuous wetting and drying of lead can distort the patina and trigger *intergranular* corrosion (see section 3.3) (Black and Allen 1999). Lead objects in stratified contexts are often found in relatively good condition (Tylecote 1983, 403). However, this bias in data is now changing with the prevalence of metal detected assemblages and the recording by the Portable Antiquities Scheme (PAS) which is seeing an increasing number of lead artefacts in poor condition. Lead antiquities form a significant part of the archaeological record and great variations in preservation has been noted in assemblages, though little has been done to tackle their conservation (Foard 2012, 117-119).

Gilbert's study concluded that the greatest corrosion in lead (pipes) takes place in moist acid clays and moist acid peats (Gilbert 1946, 163). He revealed that lead can suffer severe localised corrosion along horizontal grooves whilst buried in soil. Significantly, he observed that in environments below pH 4.5 the condition of lead can deteriorate rapidly and in acidic clays it would not be expected for lead to survive in its buried form for more than a few years. However, he does reiterate that it is not possible to associate the corrosion process with a single soil characteristic, highlighting that it is the combination of parameters which form an aggressive soil environment (Gilbert 1946, 171).

Foard assessed a sample of lead bullets from 17th-century conflict sites and concluded that the main factors affecting their condition were soil pH, soil type and their land use history (Foard 2012, 117). Bullets residing in neutral to slightly alkaline clay with little agricultural disturbance were in the best condition, whilst bullets on more acidic, free-draining sandy soils under cultivation were in much poorer condition (Foard 2012, 153). He based his assessment of bullet condition on their remaining surface detail and potential stability or level of 'surface erosion'. Bullets in *good* condition still retained surface features preserved in the corrosion layer, whereas those in *poor* condition had a heavily damaged surface and had obscuring corrosion products (Foard 2012, 117-119). However, Foard's assessment was brief and only looked at a limited number of factors pertaining to the burial environment, whilst failing to measure the condition of artefacts in any objective or measurable way. A more systematic approach to assessing condition of objects needs to be developed that can later be extended to examine other artefacts classes and metal types.

2.1.2 Site management and monitoring

To date, one of the main approaches to conserving buried archaeological assets is to preserve archaeological remains *in situ*. As a result, sites have been monitored in order to assess threats to the archaeological record and ongoing degradation processes. A significant example in the UK is when remains of the Rose Theatre were exposed during construction work in London in 1989. The iconic importance of the site led to the remains being preserved *in situ*, leading to one of the first managed and monitored reburial programmes in England, with the exception of Flag Fen near Peterborough (Corfield 2004). Due to its situation on peat beds and silty clay it was necessary to keep the site of the theatre continuously wet so the clay did not crack and promote destabilisation. The site was covered with layers of chemically benign sand and saturated to preserve the organic remains. Monitoring through dipwells of pH, redox, conductivity and temperature continued and the programme was effective in the medium term for preservation of the waterlogged site. This project brought to light the huge complexities surrounding the burial environment and led to a variety of other research programmes (Corfield 2004; Corfield *et al*. 1996; Nixon 2004)..

However, the great majority of monitoring programmes have focused on waterlogged burial environments for the preservation of organic materials in stratified contexts, and not on unstratified deposits in oxygenated soils such as in ploughsoils (Caple, Dungworth, and Clogg 1997; Huisman and Mauro 2012). Work carried out in this current study will shed light on the plausibility of preserving topsoil deposits *in situ* and assess what level of threat they face from deterioration.

2.1.3 Good versus poor environments for preservation

From the above discussions a number of significant soil attributes can be identified as being influential in the preservation of metals below ground and it is clearly a combination of soil factors which lead to metal deterioration. Some research has been able to highlight individual parameters as having the most impact on the condition of buried metals in particular environments. Potentially poor versus good environments in terms of preservation is reviewed in table 3. The general consensus is that acidic soil with high water content, high conductivity, high organic content, and the presence of soluble salts such as nitrates and chlorides will be corrosive environments. The main area of disagreement between researchers is surrounding soil type and its effects on metal preservation. Some have found sand to be poorly preserving environments, whilst others deem clay as most aggressive. Most commonly, the best environments for the preservation of metals are anaerobic and alkaline, though these types of environments are not often found in ploughsoil deposits. Theoretically the most preserving environments for lead are dry alkaline environments, avoiding acidic conditions and high organic contents.

Potential corrosion level	pH	Conductivity	Water content	Organic content	Texture	Soluble salts
High	Extremes 5.5<8.5. Lead can degrade very quickly <4.5	Corrosion increase as conductivity increases, particularly >200μS	Aggressive over 20%. Corrosion increases with water content, up until near saturation.	Corrosion increases with organic content, particularly >20%	Well drained coarse textured soil (sands)	High levels of soluble anions (chlorides, nitrates etc.)
Low	Near neutral 6-8.5	As low as possible <100 μS	Low water contents <10-15% (or waterlogged environments)	Low organic contents <10%	Poorly drained fine textured soils (clays and peats)	Low levels of soluble anions

Table 3: Summary of main soil characteristics affecting corrosion levels. Adapted from Gilbert (1947), Booth *et al.* (1967), Corcoran *et al.* (1977), Adams (1994), Wilson (2004), Historic England (2016c).

2.1.4 Overview of the corrosion of metals in soil

The above discussion highlights previous research into the corrosion of metals and the relationship between their deterioration and their burial environment. Soil chemistry has a clear impact on the preservation of buried assemblages and several soil parameters have been successfully highlighted as significant indicators of soil corrosivity, including soil type, pH, conductivity, drainage, organic content, water content, presence of solutes and fertilisers, and redox potential. For lead, the most significant soil parameters appear to be pH and soil type. Lead is particularly sensitive to pH and in very acidic environments <4.5 the corrosion of lead increases.

Attempts have been made to correlate soil parameters directly with the decay of metals in the ground. However, few have applied a systematic condition assessment of the artefacts alongside the assessment of the burial environment. Many studies have also failed to take into account the historic land use of the sites and the impact long term cultivation may have had on the condition of buried assemblages. By combining assessments of soil conditions and land use, a fuller picture of the historic burial environment can be established and the impact these parameters have on the long term preservation of buried metal assemblages can be fully evaluated. Though some of the sites used in this study do provide fully extensive land use data, sites with well documented historic land use are required in future to establish the true character of the landscape since the deposition of material in the ploughzone.

2.2 Land use and the ploughzone

The ploughsoil is distinct from lower stratified soil layers as it is regularly disturbed by agricultural activity. The main two threats to assemblages residing in topsoils are the displacement of artefacts and the damage to artefacts, both by chemical and mechanical processes in the ground. The movement in the ground through cultivation processes allows artefacts to be disturbed and re-deposited in new soil environments, resulting in damage and the formation of new corrosion cells on metallic objects. It has been shown that ploughing causes abrasion to various materials over the long term and can reduce the size of objects, resulting in the deterioration of artefacts. Increasing use of farmland for arable crops and the introduction of modern farming machinery and processes has also played a significant part in the last few decades in the deterioration of archaeological buried assemblages.

2.2.1 What is the ploughzone?

The *ploughzone, ploughsoil* or *topsoil* is the upper 0.20-0.30m of the soil column that has been disturbed by agricultural activity (Historic England 2015b). The purpose of ploughing is to prepare a field for a crop; to prepare the soil, control weed growth, fertilise the soil and break up the soil structure improving drainage (Lambrick 1977, 1). Objects enter the ploughsoil either by the ploughing in of deposits from the surface into the ploughsoil, or the ploughing of stratified buried features upwards (Millett 2000, 216). In reality, the ploughsoil is a constantly changing environment, both chemically and physically. Agricultural practice brings new artefacts into the ploughzone, whilst at the same time abrades, fragments and homogenises the material within the soil (Millett 2000, 216). As a result, ploughing damages artefacts, through abrasion and breakage of objects and through the alteration of soil environments (Oxford Archaeology 2002, 7).

As some material is brought into the ploughsoil from deeper deposits and objects have therefore lost their original context, the ploughsoil is often stripped away and not fully researched, mainly to save time and resources during archaeological investigations (Haselgrove, Millett, and Smith 2007, 2). However, this does not take into account the presence of artefacts which have resided in the topsoil since deposition and can result in huge losses of data to the archaeological record. Few areas of archaeology use the ploughsoil as their primary source of data. Battlefields are an exception where objects from periods of conflict typically reside permanently in the ploughzone where they were dropped during the battle (Pollard 2009, 181). The topsoil is the most significant archaeological layer on fields of conflict (Sutherland 2004, 15). Wilkinson *et al.* reiterate that sites containing only buried materials are of no lesser archaeological importance than upstanding monuments and their future survival should be of significant consideration (Wilkinson *et al.* 2006, 658).

Throughout the 1950s and 1960s ploughzone data was primarily used to indicate the location of buried archaeological sites. It was thought that horizontal displacement during ploughing would have destroyed any relevant data leaving objects in the ploughzone ultimately meaningless (Dunnell and Dancey 1983). Surface collections in the ploughsoil were not accurately located or studied due to this assumption, and it was not until the 1980s that finds in the ploughzone were considered in their own right, with the instigation of projects such as the 'Archaeological Field Survey in Britain and Abroad' in 1985 (Schofield 1991, 3). Most archaeologists now acknowledge the ploughzone as a 'context' and identify the layer and its contents as holding a significant part of the country's heritage (Oxford Archaeology 2014). However, cultivation continues to be the single most significant factor which places archaeological monuments under Heritage At Risk (Humble and Holyoak 2014, 15).

2.2.2 Developments in agriculture

20th century ploughing is the most damaging cultivation technique for buried archaeological assemblages (Hinchliffe 1980, 11; Lambrick 1977). The easiest way to disturb and damage artefacts in the ground is through physical site disturbance and ploughing (Roper 1976, 372). The act of ploughing has been an agricultural activity since the Neolithic period, being widespread since at least the Roman period and as a result has had a significant impact on the soils of England (Bowen 1980, 38).

Early developments in farming saw the use of hoes and single share ploughs and until the 1790s humans and animals were the source of power on farms. During the Medieval period in large parts of England cultivation was based around *open field systems* where communities ploughed subdivided fields, comprising parallel groupings of long narrow strips. These strips are represented by ridge and furrow, where earthworks survive in the landscape. By the 16th and 17th centuries, enclosure was well underway in many regions, seeing the communally held land divided up with hedges or other boundaries to create fields, often leading to large scale conversion from arable to pasture. The process was completed from the mid-18th century onwards under the Parliamentary Enclosure Acts (Curwen and Hatt 1953, 85-89).

Since the 19th century agriculture advanced immensely in terms of mechanisation and production. These changes are largely a result of the post war British Agricultural Policy, outlined by the Agriculture Act 1947. The Act promoted UK farming self-sufficiency in food production after the austerity of the war. It also increased grants and subsidies to encourage investment in agriculture, with a resultant increase in arable land in Britain (Robinson and Sutherland 2002, 161). These aims continued to be encompassed by the Common Agricultural Policy with Britain's accession in to the European Economic Community (EEC), now the EU (European Union), in 1973. The result of which has been a continuous yield increase in cereal since the 1940s (Bowers 1985, 75).

The Agriculture Act 1947 also introduced incentives to encourage an increase in the use of machinery on farms to increase efficiency and yields (Robinson and Sutherland 2002, 161). The 20th century brought new machinery and innovations to farming practices, including large and heavy tractors, rotary cultivators to chop and throw clods of soil, and subsoiling machinery for breaking up compacted earth below the topsoil, which was still a relatively new technique in the 1970s (Lambrick 1977, 7). Heavier machinery and tractor-mounted cultivation equipment which came into use in the 1930s increased soil compaction and the subsequent over-ploughing of soft lose soils (Nicholson 1980, 25). The last few decades has also seen an increase in the use of land for arable crops. Between 1950 and 1980 600,000 hectares of additional farmland were brought into cereal production, By the 1990s, 72% of England was agricultural land, 30% of which was under arable cultivation (Darvill and Fulton 1998). By 2015, 8,992,000 hectares were farmland, 52% of which was arable, indicating a substantial increase in arable cultivation (Defra 2017).

One of the most significant changes to agriculture was the development of chemical fertilisers in the 1840s, which only came into common use on arable land after World War Two, coinciding with a decline in the labour force and the increasing use of machinery. By the 1950s pesticides, herbicides and chemical fertilisers were in regular use to increase crop yields (Grigg 1989, 158). Worldwide fertiliser usage continued to increase from less than 20M tonnes in 1950 to nearly 140M tonnes in 2000 (International Fertilizer Association 2017; Wilson 2004). Nitrogen content in fertilisers also increased exponentially from 1945 onwards as it was identified as the dominant nutrient plants require for health and growth (Grigg 1989, 76).

These advancements in machinery, the increasing use of fertilisers and the conversion of more land to arable cultivation will ultimately have had a dramatic impact on the condition of buried assemblages on archaeological sites.

2.2.3 The impacts of agriculture on archaeological assemblages

Long term pasture is widely recognised as the best form of land use for the preservation of archaeological monuments; grass is not deep rooting and soil disturbance is kept to a minimum, allowing material below the soil level to remain in benign conditions (Darvill and Fulton 1998, 174). Cultivation can appear to have both positive and negative effects on the archaeological record, with the majority being negative. Beneficially, ploughing brings objects to the surface enabling more objects to be discovered which improves understanding of the archaeological record. Many sites have been identified from objects being brought to the surface through ploughing (Pollard and Oliver 2003, 120). The Portable Antiquities Scheme (PAS), established in 1997, has become the first point of call for amateur metal detectorists to record finds from England. The scheme has recorded over one million artefacts and has greatly improved our understanding of the English and Welsh archaeological record.

However, ploughing brings a lot of negative effects and a large proportion of the buried archaeological record is, or has been subjected to some form of agricultural manipulation. On arable land it is not just the top few centimetres of soil which is utilised as on pasture, but the whole of the topsoil layer, and ploughing ultimately gradually destroys data by displacement, abrasion and accelerating corrosion by altering the equilibrium between an object and its environment (Dunnell and Simek 1995, 305). The use of heavy machinery can compact the ground causing drainage issues; the 'Trials' project revealed that the pressure from farming vehicles has a much greater impact on soil compaction than the act of dragging a plough through the soil column. This could be rectified by decreasing inflation pressure in tractor tyres which would also reduce the need for subsoiling (Trow and Holyoak 2014). Ploughing also aerates the soil encouraging the displacement of artefacts and exposes assemblages to increased levels of oxygen, encouraging the process of active corrosion (see section 3.3). 52% of English farmland is under arable cultivation, which has increased by 22% in the last 20 years, indicating that agriculture poses a huge threat to the future preservation of the buried archaeological record (Defra 2017; Darvill and Fulton 1998).

Chemical damage also threatens the condition of buried metallic assemblages. Work at the University of Bradford concluded that one of the greatest threats to buried metallic assemblages is changes in soil chemistry (Foard, Janaway, and Wilson 2010, 5). As Cronyn highlights, the most significant deterioration of metals results is chemical rather than mechanical damage (Cronyn 1990, 165). Therefore, it is not just the physical damage imposed by cultivation that needs to be considered, but the changes cultivation brings to the chemical balance of the soil environment.

2.2.3.1 Artefact displacement

Artefact displacement ultimately affects how ploughsoil data is interpreted. This is also likely to affect rates of corrosion; if an artefact is being moved around the soil matrix its environment is constantly changing, being subjected to increased oxygen levels and resulting in the development of new corrosion cells encouraging the deterioration of the material (see section 3.3).

Early studies into ploughzone archaeology focused on the distribution and displacement of artefact assemblages by tillage processes; usually with a focus on ceramics or lithics (Navazo and Diez 2008; Schiffer 1996; Schofield 1991; Ammerman and Fellman 1978; Reynolds and Schadla-Hall 1980, 114; Halkon 2001). Ammerman carried out an experiment into the lateral displacement in the ploughzone; the first long term study of its kind (Ammerman 1985, 33). 1,000 small ceramic tiles were placed in the ploughzone in order to document edge-damage and displacement in the field after six years of cultivation. On average the tiles moved a distance of 2.19 metres, with an exceptional case of one tile moving 9.80 metres (Ammerman 1985, 38). The majority of displacement occurred downslope, indicating a correlation between slope and object movement. Other studies also concluded that most displacement occurs in the direction of ploughing and downhill slopes will increase this effect with minimal displacement occurring on flat land (Roper 1976, 373-374; Haselgrove 2007, 8). Others have also shown that lateral displacement will reach an equilibrium when objects begin to shift back towards their original locations (Odell and Cowan 1987, 481).

Dunnell (1990) reiterates that the size of the object and the type of soil also has an impact on the displacement of objects in the ploughzone. He concluded that larger objects tend to be displaced to a greater degree than smaller objects, and objects move quite freely in light sandy soils whereas objects may move as *peds* (blocks of combined particles) in heavy clay soils bound to the soil rather than as individual objects (Dunnell 1990, 593). This could be significant when looking at the preservation of objects in clay soils as if they move with their surrounding soil adhered to them, the surrounding environment may not be significantly altered enough to promote an increase in corrosion.

Movement of artefacts can also be vertical. In long term pasture, artefacts graduate further down the soil column with time, aided by bioturbation. Worms ingest mineral soil and organic matter and form burrows and castings which brings 1-10mm of soil per year up to the surface. Artefacts placed on the surface will sink rapidly in the first few years of deposition and fall down worm burrows, but will eventually reach a soil level where worms are not transporting the material upwards through their formation of casts (Canti 2003). The depth artefacts can reach often results in reduced detecting recovery rates on pasture sites (Foard 1995, 20) and is likely to promote the preservation of materials. However, regular cultivation will disrupt this process.

This thesis focuses on lead bullets from battlefield sites, which are very small in terms of an object type. From the above discussion it is implied that horizontal displacement of lead bullets will be minimal on flat cultivated land due to their small size (roughly 10-20mm diameter), though movement may increase with changes in slope. Displacement is likely to have occurred to some extent over the last 350 years on sites discussed in this project, but exploring this in depth is beyond the scope of the current study.

2.2.3.2 Artefact damage

Agriculture not only displaces artefacts in the topsoil, but can drastically harm the condition of objects. In the 1980s a survey was carried out at Maxey in Cambridgeshire in order to compare the condition of ceramics in the ploughzone to sub-surface ceramics. It was one of the first highly intensive surveys of ploughzone data where each find was accurately located and recorded (Crowther 1983; Millett 2000). Heavily tempered and low-fired ceramic fabrics had not survived well in the ploughsoil due to agricultural abrasion and weathering. This indicated that the type and nature of the material has an effect on the amount of damage inflicted by the plough. Halkon's work also showed that ploughing and de-stoning of fields reduces the size of pottery sherds in the ploughsoil (Halkon 2001, 9).

Haldenby and Richards (2010) analysed the survival of Anglo Saxon copper strap ends and pins from ploughzones and stratified sites across the Yorkshire Wolds. They found that ploughing promoted bending, fracturing and breaks in artefacts as well as a reduction in length of pins (Haldenby and Richards 2010).

Cultivation can also affect the rate at which metal decays in the ground. Ploughing churns and aerates the soil, increasing oxygen flow through the soil matrix allowing electrochemical processes (i.e. oxidation) to occur more readily. Any alteration to the chemical attributes of the soil will damage the equilibrium between the soil and the buried artefacts, often resulting in accelerated rates of corrosion. As oxygen increases and humidity decreases, water evaporates from the metal and passive ions from the soil solution will settle on the metal surface or cracks on the surface allowing new corrosion reactions to take place. The increasing use of agrochemicals on arable fields over the last 50-70 years has introduced more ions for metal artefacts to react with, thereby increasing corrosion rates (see section 3.3) (Foard and Morris 2012, 149; Pollard *et al*. 2004).

Galliano *et al.* (1998) assessed the effect of nitrate fertilisers on the corrosion of iron objects under simulated laboratory conditions. Fertiliser was added to sandy soils over one month and it was shown, particularly in well aerated soils, that the addition of nitrates severely increased the corrosion rate (Galliano, Gerwin, and Menzel 1998, 90). Simulations carried out at the University of Bradford also concluded that fertilisers increased the corrosion potential of metals, particularly fertilisers containing potassium chloride (Pollard *et al.* 2006). Though these projects did not quantify the level of fertilisers required to cause significant damage to artefacts, they do provide useful insights into the damaging effect applied fertilisers can have on buried metals.

2.2.4 Management of sites under the plough

The threat of damage to sites from agriculture is far from a new issue, but in the last few decades work has resulted in improving and developing mitigation strategies to manage and help reduce threats to sites. The Ancient Monuments and Archaeological Areas Act 1979 made strides in protecting archaeological sites, but did little to address the issue of the threat from cultivation. It was not until the Monuments at Risk Survey (MARS) in 1995 that the impact archaeology faced from arable cultivation was systematically quantified (Darvill and Fulton 1998). The report sampled 5% of England's known archaeological sites on farmland and concluded that agricultural processes over the last 50 years had the single greatest impact on the damage to archaeological sites in England, in some cases completely destroying scheduled monuments (Trow and Holyoak 2014, 56). It also revealed that 65% of monuments on arable sites were at medium or high risk of future damage from cultivation (Oxford Archaeology 2002, 5).

In 2001 the Department for Environment, Food and Rural Affairs (Defra) commissioned Oxford Archaeology to undertake the 'management of archaeological sites in arable landscapes project' (Oxford Archaeology 2002). The report identified the types of damage inflicted on sites in arable landscapes and highlighted the main threats to sites in cultivation as: gradual flattening of earthworks; deep cultivation and subsoiling; disturbance, breakage and chemical deterioration of portable antiquities (Oxford Archaeology 2002, 2). The report suggested two strategies to reduce damage; to revert land to grass, or to adopt 'archaeologically benign' methods of cultivation which will reduce damage to buried archaeological remains (Oxford Archaeology 2002, 21). This supported Lambrick's work who suggested the two main threats to buried assemblages was the cultivation of previously unploughed sites and the increase in plough depth of existing arable sites (Lambrick 1977).

The 'Trials' project built on the work of Defra by carrying out experiments into the viability of minimal cultivation techniques on arable land to reduce the damaging impact on the buried archaeological resource, including the damage and breakage of artefacts underground. Cranfield University conducted experiments to test the effects of ploughing on the compaction of walls, features and glass beads artificially placed in the ground (Trow and Holyoak 2014). Suggestions to improve cultivation methods on sites to reduce the impact on archaeology included: keeping heavy loads off site and using dual tyres to reduce soil compression; limit deep mouldboard ploughing; promote minimal inversion tillage and direct drilling to reduce the impact to soil disturbance (Oxford Archaeology and Cranfield University 2010). The project revealed that in certain cases sites may remain in cultivation and not be subjected to significant risk of degradation or loss, as long as the method of cultivation is suitably tailored to the archaeology (Humble and Holyoak 2014). However, this project focused on structural remains and physical damage and did not fully take into account chemical damage to artefacts below ground.

Reversion to grassland is the most effective way to reduce the impact of ploughing, but this is not often optimal, can be an expensive process with agri-environmental subsidies and is not always an attractive option for farmers (Lambrick 2004, 192). Minimal cultivation can be very effective at reducing risk of damage that can conserve archaeological sites without deep soil disturbance (Oxford Archaeology 2002, 21; Hinchliffe and Schadla-Hall 1980). In terms of archaeological data, it is the prolonged impact on artefacts from agriculture that is the issue and steps need to be taken to reduce the severe impact cultivation processes have on the ploughzone.

In 2003-5 English Heritage and Defra collaborated on the 'Conservation of Scheduled Monuments in Cultivation' project (COSMIC). The project was carried out to examine the risk of cultivation to scheduled monuments. The results of this project now form a main strand of English Heritage's 'Heritage at Risk' initiative (Oxford Archaeology 2010, 2; English Heritage 2008). COSMIC identified plough depth as an issue, rating potato crops as a serious threat to archaeological sites due to the depth of cultivation. Ongoing work by Foard has also shown that potato cultivation and de-stoning of fields can have damaging effects to battlefields and can disperse artefacts by up to 15 metres in a single episode (Halkon 2001, 7; Foard Unpublished,-b). Registered and unregistered battlefields alike continue to be cultivated in this way, as can be seen at Marston Moor battlefield (figure 2).

Figure 2: Deep potato trenches within the registered extent of Marston Moor battlefield, Yorkshire, photograph taken April 2016. .

2.2.5 Overview of land use and the ploughzone

It is clear that, in terms of land use, agriculture poses the greatest threat to the survival of buried archaeological assemblages in the ploughzone. The use of heavy machinery and fertilisers on arable land has accelerated the deterioration of archaeological metals in the last few decades and the displacement and damage of artefacts is an ongoing issue. Studies have investigated the viability of altering cultivation regimes by reverting land to pasture, applying minimal cultivation techniques, and reducing soil compaction by using dual tyres on tractors. However, studies have focused on physical damage inflicted on assemblages and structures and what has not been addressed in these experiments is the chemical deterioration of metal artefacts and the impact cultivation has on their condition and corrosion trajectory.

This study will attempt to establish whether land use is the overarching factor which affects the condition of metal artefacts in the ploughsoil, by examining land use history against the soil conditions and superficial geology of sites. This will enable mitigation strategies to be adapted for specific burial environments to help preserve the buried archaeological resource. It will also enable decisions to be made as to whether artefacts can be preserved *in situ* in particular environments, or whether they are deteriorating at an accelerated rate and need to be prioritised for research or rescued from their burial environments.

2.3 Soils

Soils play a significant role in preserving cultural heritage assets, but can also lead to their deterioration (Davidson and Wilson 2006). It is important to assess the soil in which materials reside as it has formed their core environment for hundreds of years. As a result, soils will have affected the decay process of artefacts. Studying soil parameters is vital in order to identify which parameters have a greater impact on the preservation or deterioration of buried metal assemblages.

2.3.1 The study and classification of soils

Soils are very complex systems which evolve and develop over time, responding to and influencing environmental conditions (Gerrard 2000, 2). They are the key ingredient that makes up the burial environment for artefacts beneath the ground. Crucial to this current research is an understanding of the effect variations in soil properties can have on the aggressiveness of soils towards metallic artefacts.

The scientific study of soils developed in the late 19th century when Dokuchaev brought together the work of agricultural scientists, chemists and geologists to demonstrate that soils were continually developing through soil-forming processes, establishing the soil *profile* as a way of systematically studying these processes (Hodgson 1978, 1). Over the decades various systems have been devised for the study and classification of soils, one of the most important being the 'Soil Survey Manual' compiled by the United States Department of Agriculture (U.S.D.A), first published in 1937. The concepts laid out in this handbook are still widely used and adapted by soil scientists across the world (Hodgson 1978; U.S.D.A. 1993b).

In England and Wales, Clarke's 'The study of the soil in the field' (Clarke 1971) acted as a guideline for many years. Most soil description and classification research in England and Wales is now based around the methods and concepts laid out in 'Hodgson's Soil Survey Field Handbook' and Avery's system of soil classification (Avery 1980; Hodgson 1976; Adams 1994, 43; Cranfield University 2007). However, no single system covers the range of different soil types a researcher is likely to come across (Wilmott and Jack 2006, 331). There are 119 soil types at sub-group level (e.g. podzols, gleys) and many studies apply these classifications without measuring individual physical and chemical characteristics of the soil (Adams 1994, 43). The work in this thesis covers a number of physical and chemical soil attributes and classifies them thusly, as opposed to forcing them into a type. Soil classifications can encompass huge variations in pH and other attributes and when looking at soil samples in detail this classification system is of limited use and therefore will not be applied in this study.

2.3.2 The nature of soils

Soils are formed through various processes: from the breakdown of rocks and minerals into smaller particles; through the interaction of minerals in water to produce altered or new minerals; or through biological processes and the decay of organic matter (Rowell 1994, 18). Soils are composed of a mixture of parent material, materials that have been chemically altered through precipitation, and organic matter (or humus) (Cornwall 1958, 75; Wilmott and Jack 2006, 331). The parent material of a soil may be the material underlying the soil, or may have been transported from elsewhere through colluvial, alluvial, or aeolian processes (English Heritage 2007). These mineral and organic components are in turn mixed with living organisms, air, water, and dissolved salts to form the soil matrix (figure 3). Therefore, the character of the soil is linked to a number of environmental factors including climate, vegetation, water content, slope and exposure, soil organisms and parent material (Cornwall 1958, 76; Rowell 1994, 1).

Alongside these soil characteristics are ecological processes. Bioturbation is a natural process where living organisms disturb soil sediments. Earthworms reform the soil matrix by pushing, sorting, digesting and casting soil and are usually plentiful in topsoils due to the high organic content. This is important for archaeological artefacts as worms deposit 1-10mm of soil on the surface every year and this increases the depth of artefacts by 0.10-0.25m over the lifetime of an object (Canti 2003, 141).

2.3.3 Soil attributes

Characterising a soil requires the analysis of a number of different soil attributes. As discussed above, this is particularly true in establishing corrosivity of a soil in order to relate the burial environment with the survival of materials (section 2.1). Many soil properties are very closely linked and small changes to one property may affect another; for instance the structure of a soil affects its porosity and its porosity affects the total water holding capacity of the soil (Rowell 1994, 79). This is why it is important to carry out a combination of soil analyses to understand the dynamics and character of the soil system. Key physical and chemical soil properties to analyse in order to characterise soils will now be discussed in turn. Chapter 4 describes the techniques and methods used to analyse soil samples in this study.

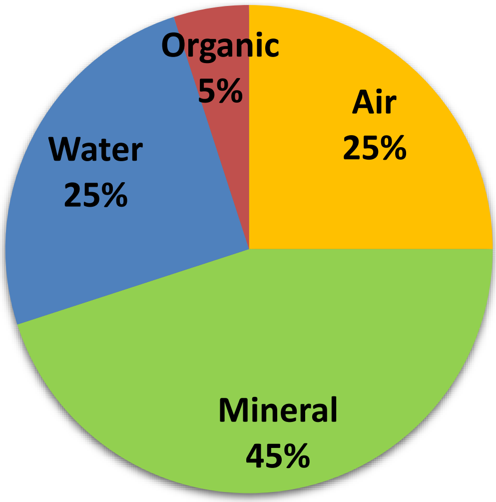


Figure 3: Major components of soils showing average contents of each component. Adapted from Brady and Weil (2002, 17).

2.3.3.1 Soil colour

The three main factors which influence soil colour are organic matter content, water content, and the presence of iron and manganese oxides (Brady and Weil 2002, 122).
Soil colour can be used to diagnose oxygen permeation in soils as well as general organic content. Well drained and oxidised soils tends to be reds or browns whereas waterlogged reduced anaerobic soils tend to be greens, blues and greys (Wilmott and Jack 2006). Ploughsoils are generally darker in colour due to the accumulation of organic matter (Gerrard 2000, 39). Colour matching is not an exact science and everybody sees colour slightly differently which needs to be taken into consideration, though the standardised Munsell system used worldwide aids repeatability and accuracy of the method (Munsell Color 2000).

2.3.3.2 Soil texture

Particle sizes are grouped into sands, silts and clays, the proportion of which determines the overall soil texture (table 4). The structure of the soil is also very important; sandy soils tend to be granular with large pore spaces between them allowing easy flow of oxygen and water through the soil (figure 4). Clay particles are plate-like and are prone to compaction, often with restricted drainage and oxygen flow. They are also prone to swelling as water passes through clay crystal structures and is attracted to cations on the surface of clays, resulting in a high water-holding capacity (see section 2.3.3.3). Soils with a fairly even mix of particle sizes are called loams and are generally well suited to crop production (Brady and

Weil 2002, 123; Rowell 1994, 19-20). When the proportion of sand, silt and clay is known the class of soil can be identified on a soil texture triangle (figure 5, table 5) (Head 1980; U.S.D.A. 1993a).

Particle	Size (mm)
Stones	>2mm
Coarse sand	2-0.2mm (2000-200μm)
Fine sand	0.2-0.06mm (200-60μm)
Silt	0.06-0.002mm (60-2μm)
Clay	<0.002mm (<2μm)

Table 4: Particle sizes from the UK classification system; the US system uses 50μm as the cut off between fine sand and silt (Rowell 1994; U.S.D.A. 1993a).

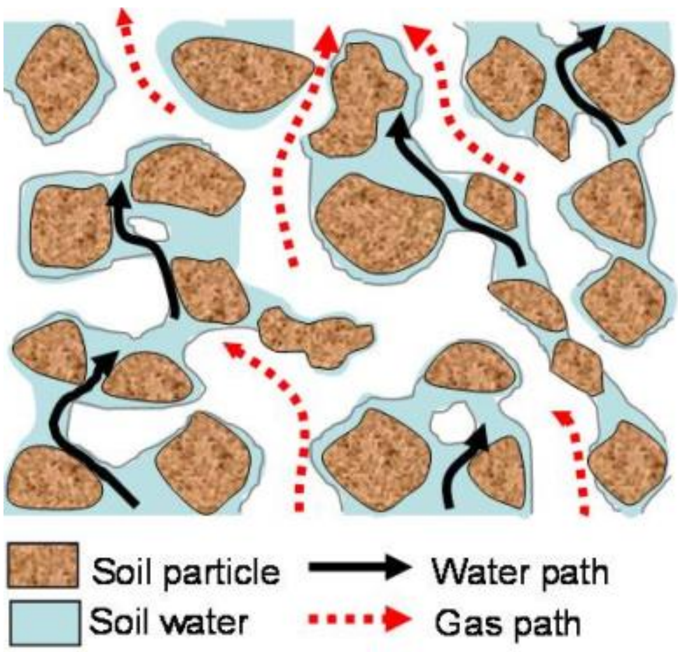


Figure 4: Visualisation of soil pore spaces (Aarhus University 2017).

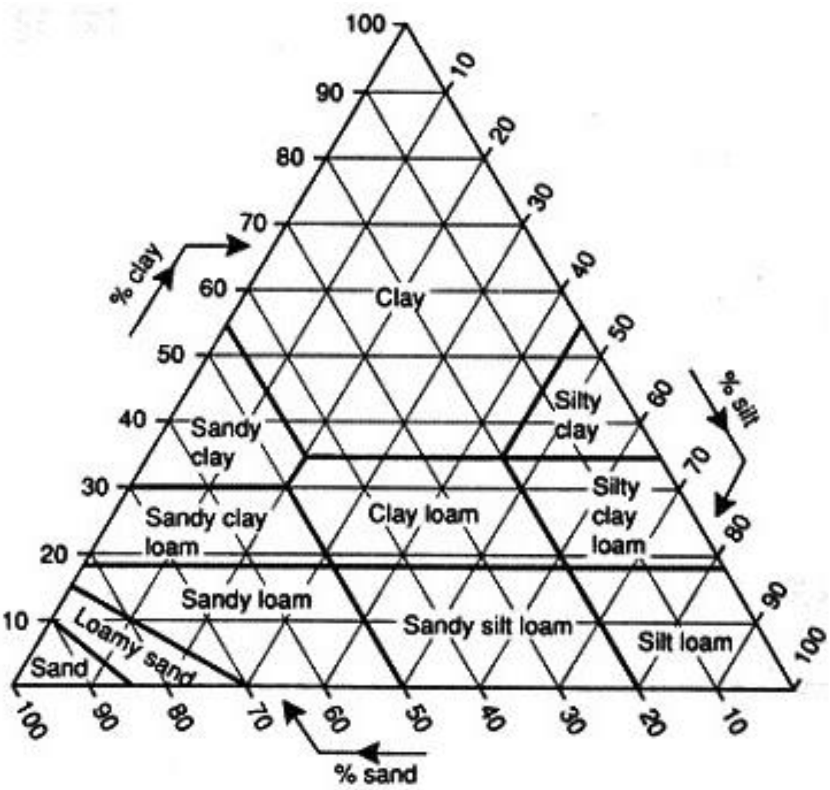


Figure 5: European/UK texture triangle for clay, sand and silt ratios, applied in this research (Cranfield University 2017; Rowell 1994, 28).

Soil type	Texture	Soil textural class
Sandy soils	Coarse	Sand
		Loamy sand
		Sandy loam
		Loam
Loamy soils	Medium	Sandy silt loam
		Silt loam
	Moderately fine	Sandy clay loam
		Silty clay loam
		Clay loam
		Sandy clay
	Fine	Silty clay
Clayey soils		Clay

Table 5: Soil texture in relation to soil textural classes.

2.3.3.3 The colloidal fraction

The clay and humus content of soil is known as the colloidal fraction and contains the smallest soil particles in the matrix (Brady and Weil 2002, 316). Soil colloids give the soil an enormous amount of reactive surface area due to the number and small size of the particles which allows particle surfaces to adhere to ions including plant nutrients and salts due to the charge on clay molecules. The fraction also give soils the ability to absorb water causing swelling (Rowell 1994, 21).

Clay has a much greater impact on soil texture than sand or silt. A soil only has to contain 35% clay to be classed as a 'clay', whereas to be deemed 'sand' it requires a content of 85% sand (Rowell 1994, 28). Clay minerals are formed of successive planes of oxygen and hydroxyl ions bonded with silicon, aluminium, magnesium and other cations into tetrahedral or octahedral sheets which form crystalline hydroxyl silicates (figure 6). They are generally plate-like in structure, range in sizes <2µm and vary in surface area, structure, electrical charge and swelling characteristics (Rowell 1994, 21-25). Electrically balanced clay would have an equally balanced charge between electropositive ions and electronegative ions, but soil clays contain impurities which alters this charge. Due to this an exchanges with other cation on the surfaces of molecules, clays usually have a negative charge (Rowell 1994, 26; Brady and Weil 2002, 317).

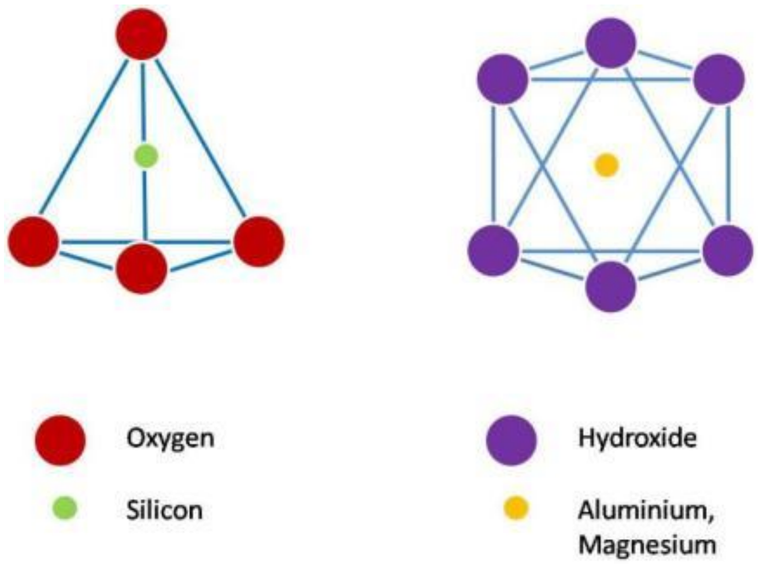


Figure 6: Molecular structure of silicate clays showing a single tetrahedron and an octahedron. In clay crystals thousands of blocks form planes of ions with alternating oxygen and hydroxyl groups. Adapted from Brady and Weil (2002, 322)..

The most important reaction in the colloid is the exchange of positive and negative ions (cations and anions) between the soil solution and the surface of the soil colloids (Brady and Weil 2002, 316; Caple 2004, 157). Clays can readily exchange cations for other cations near the clay surface, through a process known as 'isomorphous substitution'. Cations in the clay structure can be exchanged for cations near the surface with a less positive charge, resulting in the clay developing a negative charge. As clays tend to be negatively charged, positively charged cations are attracted to their surfaces; each colloid particle, or *micelle,* attracts thousands of Al^+, Ca^+, Mg^+, K^+, H^+ and Na^+ ions (figure 7) (Brady and Weil 2002, 317). These ions are loosely held or *adsorbed* on the surfaces of colloids, not bonded, and so are easily exchanged with other ions in the soil solution. These are known as *exchangeable ions* and relates to the *cation exchange capacity* (CEC) which measures the quantity of charge on the cations held in the clay. The attractive forces between the clay molecules allow their crystal structure to remain stable. When water and other substances pass through the structure, cations are attracted to the negatively-charged clay particles, which allow retention of salts, nutrients and water, enabling clays to swell and maintain their high water-holding capacity (Rowell 1994, 24-25).

Cation exchange can be pH dependent; as pH increases and more OH^- are present, H^+ dissociates from colloids which results in negatively charged particles. When negative charge dominates the colloid, cations will be attracted to the clay surface and negatively charged anions will be repelled away in the soil solutions. In acidic clay soils where more H^+ are present, positive charge dominates the soil and negatively charged anions will be attracted to the soil, with cations being repelled (Brady and Weil 2002, 339).

Cation exchange depends on the pH and the soil texture. Sandy soils with very little colloidal fractions have a low CEC, whereas clays and organic matter have high CEC (table 6). Soils with a low pH will tend to be positively charged, neutral soils will have little or no charge, and soils with a higher pH will be negatively charged (Rowell 1994, 27). This indicates that soils with a high CEC, high organic content and high levels of clay, in an acidic environment would be aggressive due to the attraction of anions and negatively charge salts to the clay surfaces. The attraction of anions to clay surfaces would increase the salt content of the soil, creating a corrosive environment for any metal artefacts residing in the soil. This is why acidity combined with clay fractions can be a very damaging environment.

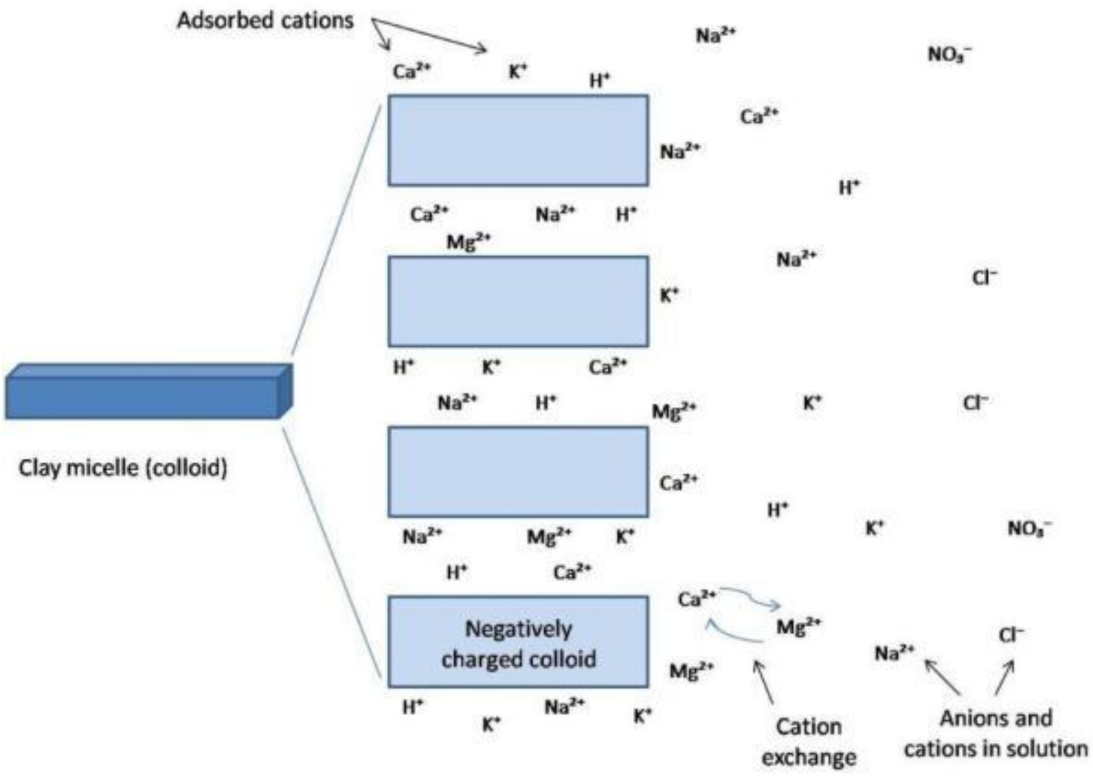


Figure 7: Silicate clay particle (micelle) forming part of a colloid fraction. The negatively charged micelle attracts positively charged cations to the clay surfaces. Anions are repulsed by the negative charge and lie in solution furthest from the clay. Adapted from Brady and Weil (2002, 318).

Material	**Cation exchange capacity (CEC) (meq/100g)**
Clays	
Kaolinite	3-15
Illite	15-40
Montmorillonite	80-100
Organic matter	200-400
Soil texture	
Sand	1-5
Loamy sand to sandy loam	5-10
Loam	5-15
Clay loam	15-30
Clay	>30

Table 6: Typical cation exchange capacity of soil components and soil types. Adapted from Smart Fertilizer (2017).

2.3.3.4 pH

pH (Puissance d'hydrogen or 'power of hydrogen') measures the balance of hydrogen and hydroxyl ions in the soil solution. All water solutions contain a mixture of positively charged hydrogen ions (H^+) and negatively charged hydroxyl ions (OH^-):

$$H_2O \rightleftharpoons H^+ + OH^-$$

If substances are added to the water the concentration is altered so that if H^+ increases, OH^- must decrease accordingly (Townsend 1973, 162). pH is measured on a logarithmic scale from 0 to 14 (Wilson 2004, 2.8). At pH 7, water is neutral and has an equal concentration of H^+ and OH^- ions. At a pH of 6 there are 10 times more H^+ ions than at pH 7, and 100 times more than pH 8 (Head 1980, 223). Neutral pH 7 is defined by water, but 'neutral' soils have a range of pH 6.5-7 (Rowell 1994, 153).

Acidic soils are high in H^+ and alkaline soils are high in OH^-. Level of acidity depends on vegetation, decomposition of organic matter, nitrification, microbial mass, the parent material of the soil, the structure of the colloidal fraction and the cation exchange capacity of the soil, as mentioned above. Acid rain and human-induced activities have altered these natural levels over time. Agricultural liming increases alkalinity, whilst pollution and fertilisers tend to raise acidity (Rowell 1994, 153). Sandy soils are more prone to acidity than heavy textured soils due to the cation exchange capacity of clay particles. Sands have a low cation exchange capacity and are usually positively charged, with little buffering capacity against acidity.

Acid corrosion is a serious problem for metals, caused by acidic compounds present in soil solutions. Darvill suggests that pH is a determinant factor in the survival or degradation of archaeological materials (Caple and Dungworth 1998; Darvill 1987) and it has been identified in many studies as having a negative impact on the preservation of metals (Wilson 2004; Fjaestad *et al.* 1998; Davidson and Wilson 2006; Gilbert 1946). British Standard guidelines for corrosion likelihood in soils states that corrosion load is lowest near neutral conditions at pH >6 and <9 (British Standard 2003, 7). Corrosion of metals is most prevalent at pH extreme <4.5 and >8.5, though Historic England rate acidic and corroding environments for metals at a pH <5.5 (Historic England 2016c, 12; Gilbert 1946). For a discussion on the effects of pH on the corrosion of lead artefacts see section 3.3.6.

2.3.3.5 Redox potential

Redox potential (Eh), or oxidation reduction potential, is a measure of the potential for electrochemical activity in a system (Caple and Dungworth 1998). It describes the tendency or ease for chemicals to be oxidised in soils and relies on the transfer of electrons from one atom to another (Wilson 2004, 2.9). Oxidation involves the loss of electrons and reduction represents the gain of electrons. In terrestrial contexts (i.e. soils), the oxidising agent is primarily oxygen, and the reducing agent is mainly organic matter (Raiswell 2001). If there is plenty of oxygen available in a soil system the redox potential will be higher. In such an oxidising environment, an electrical potential will be generated which is required for the corrosive reaction to take place between an object and its soil environment. Eh can range from around +1.0V in high oxidising environments to -0.4V in reducing environments (Bass Becking, Kaplan, and Moore 1960). Agricultural soils usually have a redox potential of between +300 and +800mV. Oxidising reactions take place readily at 400mV and over, whilst reducing reactions tend to take place below this level, affecting the type of corrosion which forms (Historic England 2016b).

Measuring redox is very difficult unless in saturated or waterlogged environments, as levels rely heavily on oxygen and water content and aerated topsoils will produce very questionable results (Historic England 2016b; Caple and Dungworth 1998). For this reason, redox will not be measured in this study.

2.3.3.6 Water content

All soils contain an amount of water, typically between 10-55% of the total soil volume. The amount of water retained in the soil column will depend on its density, drainage and water retention capacity which will vary throughout the year. Clay particles and organic matter helps to retain water in soils which is why topsoils tend to have higher water contents than lower down the soil column. Soil particles are surrounded by pore spaces which will either be filled with water or air. Moisture content is the amount of water within the pore space between particles (Head 1980, 51).

Water is essential for soil processes; it forms the soil solution which contains dissolved salts and molecules for plants and microbial life and it is where chemical reactions take place at interfaces with particle surfaces (Rowell 1994, 79). The water content also determines the mobility of salts in the ground. If the water content is low then mobility in the system will also be low as well as biological activity which can reduce the rate of decay in the soil (Caple 2004, 156). Water content also affects the availability of oxygen in the system. An excess of water can lead to exclusion of oxygen due to a lack of space in the pores for oxygen to occupy. A lack of water in a system can prevent formation of corrosion cells as mobility around the pores almost ceases and this will impede the corrosion process (Camitz and Vinka 1989).

Clays can retain water more easily as the soil particles are small and closely packed together. If soil contains expansive clay particles, water allows particles to become hydrated causing swelling and expansion of the soil, increasing their water holding capacity. The attractive forces between clay molecules help to retain water in the soil matrix. Sands are usually well drained and fail to retain water, though the large pore spaces between sand particles means that a lot of water can pass through the system in a short space of time. In reality, it is loams with a range of particle sizes that are able to hold the most water, whilst sands have the lowest water holding capacity. In terms of soil corrosivity, Booth *et al*. (Booth, Cooper, and Cooper 1967) and Corcoran *et al.* (1977) agree that a soil with water content above 20% should be deemed aggressive towards metals.

Fluctuating water levels can also have an impact on the preservation of archaeological materials. Archaeological features that lie under the water table in saturated conditions can remain stable for many years. However, lowering the water table changes the moisture and oxygen content of the soil and can alter the redox, pH and temperature of the soil which will affect the rate and nature of corrosion (Historic England 2016c, 20; 2016b). Fluctuations in groundwater levels allow materials to dry out and become re-wetted which can be particularly damaging to metal artefacts. Fluctuations should be kept to a minimum to aid the preservation of materials (Graham and Williams 2008).

2.3.3.7 Organic matter content

Organic matter will have an effect on a soil's fertility, pH, and many other properties including acting as an adhesive for the soil's structure. All cultivated soils will have organic contents and further organic matter is added to maintain structural integrity (Caple 2004, 159). Most soil will contain 1-10% organic matter, though humic soils can contain 15-25% (Brady and Weil 2002, 500). An organic soil should contain >20% organic matter (Hodgson 1978, 201), though Defra suggest organic content of 10-20% is an 'organic' soil (Defra 2010, 28).

Angelini *et al.* (1998) studied the influence of soil with a high organic and carbonate content on the corrosion rate of steel and revealed that organic content, carbonate content and water content initially increases the corrosion rate at the beginning of the burial period. This may be due to humus rich cohesive soils inhibiting the formation of passive protective corrosion layers on the metal surface (Pritchard, Hallett, and Farewell 2013, 21). Humus forms part of the colloidal fraction alongside clay particles and makes the soil reactive, encouraging the exchange of ions (section 2.3.3.3), which means soils with higher organic levels will in theory promote corrosion.

2.3.3.8 Conductivity

The corrosion of metal is an electrochemical process and depends upon the presence of an electrolyte. In the buried environment the solution within soil acts as the electrolyte and so water content is essential for chemical reactions. The ability for a soil to conduct a current depends on the concentrations of ions in the electrolyte solution. The higher the salt content and water content of a solution, the higher the conductivity level will be as it increases the ability of an electric current to flow.

Conductivity is a direct measurement of the overall concentration of salts in a given solution. A soil with high conductivity is expected to be highly corrosive (Corcoran *et al.* 1977, 474). Conductivity is measured in micro-Siemens per centimetre or deci-Siemens per metre (µS/cm or dS/m). The United States Department of Agriculture measures conductivity referring to how saline soils are, though these levels relate to extreme saline environments and not typical British soils (table 7). Wilson's scoring range for corrosivity parameters, mentioned in section 2.1, rates the corrosivity of soils based on conductivity range based on previous studies; the higher the conductivity, the greater potential for corrosion to take place (table 8) (Wilson 2004; Corcoran *et al.* 1977).

Conductivity (µS/cm)	**Salinity**
<2000	Non saline
2-4000	Very slightly saline
4-8000	Slightly saline
8-16000	Moderately saline
>16000	Strongly saline

Table 7: Soil salinity based on electrical conductivity (U.S.D.A. 2011). Note that this level of salinity is for arid environments and not for typical British soils.

Conductivity (µS/cm)	Corrosivity score
<50	0
50-100	1
100-200	2
200-400	3
400-500	4
>500	5

Table 8: Soil corrosivity scores based on conductivity (Wilson 2004, 4.8).

2.3.3.9 Presence of anions - chloride and nitrate

Chlorine and nitrogen are present in most soils and plants require the elements for nutrients and to help fight disease (Brady and Weil 2002, 655). Soils containing organic acids, chlorides and nitrates can cause severe corrosion of metals due to their solubility and ease of movement in the soil solution (Costa and Urban 2005, 53).

Most chlorine in soils is in the form of chloride ions (Cl^-) from sources including the parent material, sea water and potassium chloride (KCl), which is the most widely used potassium fertiliser; average soil concentration of chlorides is estimated at 100ppm (Schulte 1999; Flowers 1988). The general chloride content in soils across England is relatively low and in most well drained areas a high chlorine content would not be expected (UKSO 2015). High contents are likely to be from application or contamination and the overuse of potassium chloride containing fertilisers, which can lead to chlorine toxicity.

Chloride is a particularly dangerous compound as it is very mobile in solutions and research has shown chlorides can cause aggressive corrosion in metals (Gerwin and Baumhauer 2000; Nord, Mattsson and Troneer 2005; Pollard *et al*. 2004; Rimmer and Wang 2010; Turgoose 1982). Many salts cause an attack on the surface of an object, whereas chloride ions tend to cluster at grain boundaries and break through to the metal residing below the overlying passive layers. In the ground chloride ions accumulate at anodic sites at the interface between the metal and the corrosion layer which can lead to secondary corrosion of internal metal structures (see section 3.3) (McNeil and Selwyn 2001, 609). This is particularly dangerous in copper alloys as chloride ions are the main source of bronze disease which is a catalytic reaction and, as long as exposed to oxygen, will continue to corrode the metal.

Nitrogen is one of the most common soil nutrients and is vital for plant growth. All nutrients increase growth and crop yields, though nitrogen has the largest effect for most cereal crops (Addiscott, Whitmore, and Powlson 1991, 17). The recommended level of nitrate content in soils is 10-50mg/kg, and levels above 160mg/kg are considered high (Agricultural and Horticultural Development Board 2017, 23). However, recommended levels vary depending on soil texture: it is recommended for sands to have a nitrogen supply of 25-50mg/kg, whilst loams and clays should have levels closer to 75mg/kg as take up by plants is less efficient in clays (Soil Quality Pty Ltd 2018).

Nitrate dissolves in water very easily and is found in most natural waters, but concentrations of nitrate has been steadily increasing for the last few decades due to the use of nitrogen fertilisers, the most common of which in the UK is ammonium nitrate (Addiscott, Whitmore, and Powlson 1991, 1). This is in part due to food shortages following World War Two. Food production had to be increased and a way to do that was to increase fertiliser usage to increase crop yields at a time when fewer hands were available to work the fields (see section 2.2.2).

Nitrate ions do not adhere to soil particles. As clays are generally negatively charged they attract positively charged ions to their surface and negatively charged ions like nitrate and chloride are repelled (Addiscott, Whitmore, and Powlson 1991, 33). Nitrates can also become nitric acid when in solution which can be very damaging to metals (see section 3.3) (Sivilich 2016, 119). Corrosion is likely to be highest just after nitrogen application on fields before it is leached through the soil column or taken up by plant roots, and farmers often compensate for this leaching by applying more nitrogen fertiliser on to fields than is necessary as plant demands for nitrogen is high.

Studies have suggested that nitrogen has a damaging effect on buried metals, but the results vary. The fact that nitrogen is highly soluble and leaves the soil system very quickly allows other corrosive processes to dominate. The presence of nitrogen has been shown to trigger the formation of passive oxide layers on metals, protecting them from further decay (Wilson 2004). As nitrogen is the most common soil nutrient and is applied to fields in greater quantities than any other fertiliser, it is worth addressing the impact nitrogen levels in soils has on the long term preservation of buried metals. Nitrogen levels in topsoils will be examined in this study and the method used is laid out in section 4.5.1.7.2.

2.3.4 Overview of soils

Many factors contribute to the corrosion of metal underground, and simple chemical tests can confirm the nature and corrosivity of the soil. It is important to measure the acidity and conductivity of the soil, as well as the water and organic content in order to evaluate levels of soil aggressiveness. Soil type also plays a role in how metals corrode, and the presence of solutes and the application of fertilisers can also impact on the preservation of buried metals.

An acidic environment is always potentially aggressive due to the formation of soluble corrosion products (see section 3.3), and in alkaline conditions sulphate-reducing bacteria can cause decay (Head 1980, 232). The presence of chlorides and nitrates can also accelerate corrosion, as shown from previous experimental studies (Wilson 2004; Wilson *et al.* 2006). It is generally thought that anaerobic neutral to slightly alkaline environments are most suited to the preservation of metals (Davidson and Wilson 2006, 4). There is no single soil parameter that can be used to determine soil corrosivity; a number of characteristics have been identified as all playing a part in the corrosivity of a soil (Jones 1996). A discussed in section 2.1.1, pH has a particular impact on the preservation or deterioration of lead. Conditions <4.5 pH will seriously impact on the corrosion of lead artefacts. Table 9 summarises the predictability for low to high corrosion rates of lead in soils. These predictions will be used as reference when assessing each case study and its burial environment.

In order to characterise each site in this study on its potential to preserve or damage archaeological materials, a list of parameters to address is presented in table 10. Redox potential (Eh) has been omitted due to it only being routinely recorded in saturated environments and due to the difficulty in obtaining accurate results from laboratory measurements (see section 2.3.3.5). Details on how each analysis was carried out can be viewed in chapter 4. Soil attributes need to be considered in conjunction with the historic land use of sites in order to establish the impact individual parameters have had on the preservation or deterioration of the archaeological assemblages in each case. Only by fully evaluating the burial environment can we begin to understand the condition of buried assemblages and the significance, research and conservation potential of sites. Figure 8 portrays a summary of the many factors which affect the condition of lead bullets in the topsoil, which will be discussed for each site in this study.

Potential corrosion level	pH	Conductivity	Water content	Organic content	Texture	Soluble salts
High	Extremes 5.5<8.5. Lead can degrade very quickly <4.5	Corrosion increase as conductivity increases, particularly >200µS/cm	Aggressive over 20%. Corrosion increases with water content, up until near saturation. Particularly damaging where the water table fluctuates.	Corrosion increases with organic content, particularly >20%	Well drained coarse textured soil (sands)	High levels of soluble anions (chlorides, nitrates etc.)
Low	Near neutral 6-8.5	As low as possible <100 µS/cm	Low water contents <10-15% (or waterlogged environments)	Low organic contents <10%	Poorly drained fine textured soils (clays and peats)	Low levels of soluble anions

Table 9: Summary of main soil characteristics affecting corrosion levels, predicting likely potential for corrosion. Adapted from Gilbert (1947), Booth *et al*. (1967), Corcoran *et al.* (1977), Adams (1994), Wilson (2004), Historic England (2016c). .

Soil attribute		Field assessment
Soil colour	**Conductivity**	Superficial geology
Soil consistency	**Water content**	Topography
Soil texture	**Organic matter content**	Land use history
Soil depth	**Chloride and nitrate content**	
pH		

Table 10: Soil attributes analysed and field observations studied for each case study in this research.

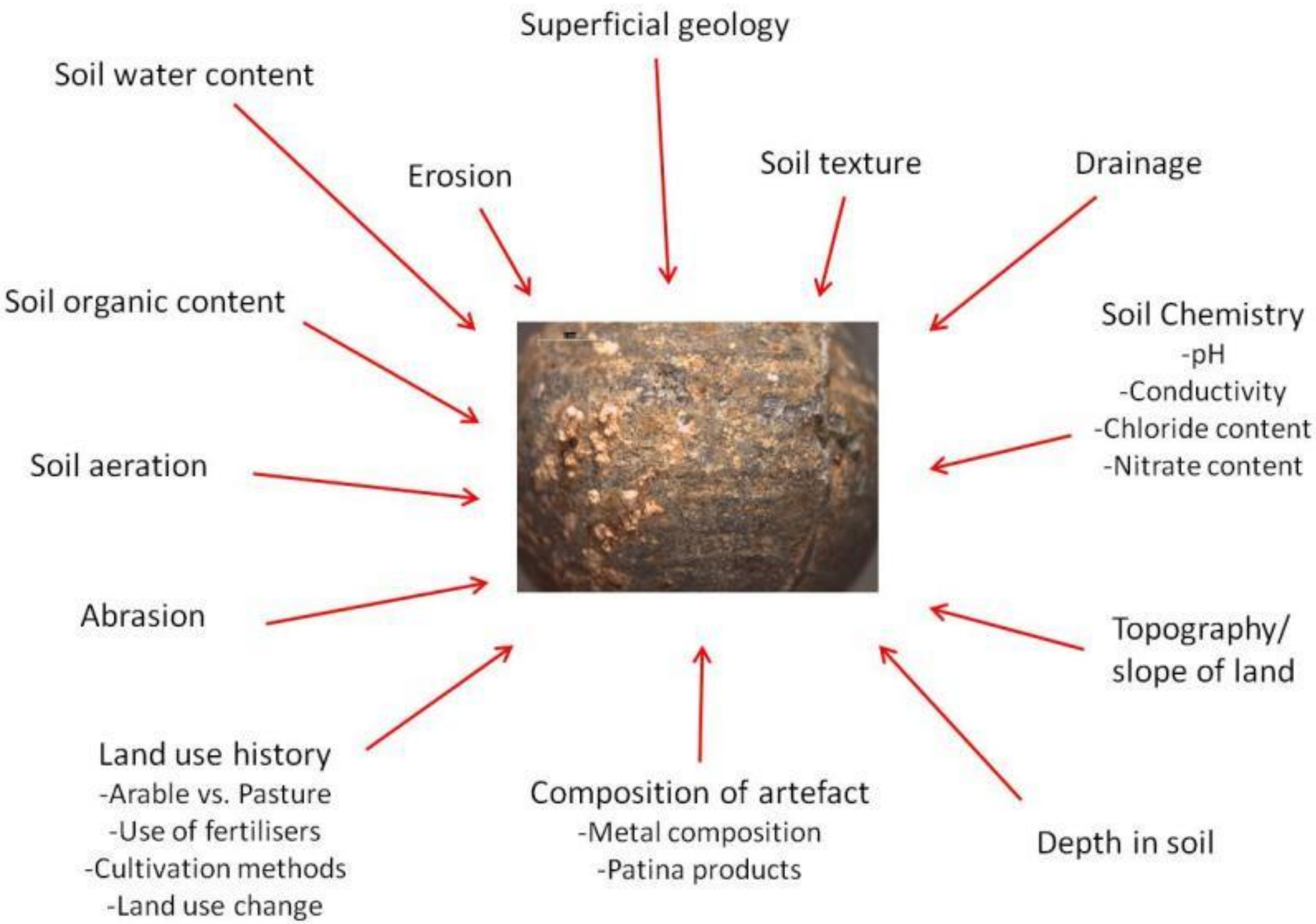


Figure 8: Main factors affecting the condition of lead bullets in the ploughsoil.

3 Selection of sites and artefacts: a condition assessment methodology

The present study seeks to develop a methodology by which the factors influencing metal artefact decay in ploughsoils can be assessed. In order to do so, a single site type was chosen which contains a ubiquitous artefact class; lead bullets on 17th-century sites of conflict in England. Attempting to assess the condition of all objects and materials from sites would be very time consuming and would require various methods of assessment as all materials degrade in different ways. The principles developed in this methodology can be applied to other sites and artefact classes in future in order to address the condition of assemblages in topsoils on a greater scale.

3.1 Sites of conflict and selection for study

Sites of conflict, encompassing battlefields and siege sites, have been chosen as the site type for investigation in this research as the majority of their archaeological data resides within topsoil contexts on British farmland, and are a key class of site under the direct threat of agriculture (see section 2.2). Three case studies have been selected for study; the battlefield of Edgehill in Warwickshire, the siege site of Moreton Corbet in Shropshire, and the siege site at Wareham in Dorset. The sites were chosen based on the following criteria:

-Presence of lead bullet assemblages in the ploughsoil

-Accessibility of collection for research purposes

-Accessibility of sites for fieldwork

-Systematic surveys already conducted with the location of artefacts recorded, in order to map condition across a site

-A range of condition states of artefacts across sites

-Recovered from differing soil conditions and soil types in order to compare soil attributes

Initial analysis of the lead bullets from each site revealed they were in varying states of condition. The sites are located in different geographical locations across England, and provide variation in land use, superficial geology and soil characteristics for comparison. Edgehill resides on alkaline clay and provides an excellent example of preserved medieval ridge and furrow earthworks on permanent pasture, though some have been lost across the site through conversion to arable since World War Two. Edgehill provides the opportunity to assess whether recent conversion to arable cultivation has had an impact on the preservation of lead bullets. An important issue is to explore whether artefacts have deteriorated to a greater extent in fields under the plough than those under pasture. Moreton Corbet lies on slightly acidic to neutral sand and displays varied historic land use; from use as formal gardens, to meadowland, with conversion to arable in the last few decades. The assemblage also exhibits a range of condition in bullets over a small landscape. Wareham resides on very acidic sands and appears to have been under almost constant arable cultivation from at least the 1840s. Initial assessment indicates the bullets from Wareham are in a poor state of condition.

These differences in historic land use, levels of acidity and soil types across the three sites may have had a significant impact on the preservation of artefacts. It was hoped that a fourth site would be examined that encompassed all the above criteria whilst also residing in acidic clays for a comparison of soil environments. Sheriffmuir battlefield in Scotland was investigated in the later stages of the project, but the assemblage retrieved from the site was minimal (24 bullets) and deemed too small a collection for effective comparison (Pollard 2006). Initial assessment of the assemblage revealed the bullets to be in fair to poor condition with eroded surfaces. This is likely to be due to them residing in acidic moorland. Unfortunately, time constraints did not allow sampling to be carried out at this site.

3.1.1 Vulnerability of sites of conflict from loss of data

Archaeological objects and sites hold their value not in a monetary sense, but in information they contain regarding their production, use, date, typology and provenance (Oxford Archaeology 2009, 2). Data can be lost from sites and artefacts in a variety of ways and this threat of loss can determine how useful they are as part of the archaeological record. Battlefields and siege sites are somewhat unusual as the majority of their data exists as scatters of unstratified metal artefacts in topsoil deposits, rather than as architectural features or stratified contexts (Pollard 2009, 181). The interpretation of battlefields depends upon the accurate recording of artefact locations across landscapes, and the loss of collections from sites greatly impedes this analysis (Foard 2012, 154).

The nature of battlefield assemblages makes them vulnerable and fragile assets as topsoil artefact scatters are easily lost, damaged or completely destroyed (Ferguson 2013b). The majority of battlefields now reside on agricultural land, and so are threatened by farming processes, erosion, and the deliberate removal of topsoils from fields through harvesting or development, meaning artefacts or whole assemblages may be removed in the process. Destruction of archaeological layers and removal of objects from burial contexts affects the archaeologist's ability to interpret sites and also destroys information which should be retained as a part of national heritage (Oxford Archaeology 2009, 2).

Battlefields suffer from little legislative protection in England (Sutherland and Holst 2005, 10). Sites containing only artefact scatters and no structural remains cannot be scheduled as they are not classed as monuments under the Ancient Monuments and Archaeological Areas Act 1979. Therefore, the majority of battlefields in England cannot be scheduled. To rectify this, English Heritage established the Register of Historic Battlefields in 1995 which highlights the value of battlefields and their significance as archaeological sites. The register does not give battlefields legal protection, but planning consent on sites is restricted and they are protected through the National Planning Policy Framework (Dept for Communities and Local Govt 2012, 30). This does not include restrictions to agricultural activities, unless the agri-environment scheme active on the land states otherwise. Therefore, many agricultural processes continue to be implemented and metal detecting with landowner's permission can still be carried out on registered battlefields, whereas metal detecting is illegal on scheduled monuments unless part of permitted research investigations (Foard, Janaway, and Wilson 2010; Oxford Archaeology 2009, 100). 13% of registered battlefields are currently on the Heritage at Risk register (6 of 46) (Historic England 2015c). Though some siege sites are scheduled due to their association with structural remains, those containing only artefact scatters do not appear on the Register of Historic Battlefields, including the two siege sites examined in this study (Historic England 2018, 30).

The main way of investigating buried metal assemblages on battlefields is through metal detecting surveys. Metal detecting grew as a hobby during the post World War Two era, but initial activities failed to accurately record data (Ferguson 2013b, 6; Pollard 2009, 182). One of the earliest documented uses of metal detectors was in 1958 on the Little Bighorn and Big Hole battlefields in Montana, USA. Detectors saw an increase in use in the 1980s, focusing on battlefield investigations. The earliest large scale systematic project took place at the little Bighorn battlefield from 1984 onwards (Connor and Scott 1998, 76-77). This increase in use in metal detectors has left sites vulnerable from those using equipment outside the law. Illicit 'nighthawking' continues to be a threat battlefields face from amateur metal detectorists. Studies have revealed that some of the most famous sites of conflict, including the battlefield of Towton in Yorkshire, have been affected by detectorists trespassing and stealing material from the ground (Pollard 2009, 185; Oxford Archaeology 2009). Other sites of conflict have been targeted through the selling of battlefield artefacts online through eBay (Ferguson 2013a, 2013b).

Work by the Portable Antiquities Scheme (PAS) and Treasure Trove in Scotland has helped to resolve issues with recording and promoting responsible detecting activities, but they are still a concern and data is still being lost from the archaeological record. This loss of data means battlefields require further study in terms of conservation, management and preservation.

3.2 Lead bullets and selection for study

The main metal types present in the archaeological record are copper, lead, iron, silver, gold and their alloys. The Portable Antiquities Scheme's database is an ideal tool for gaining insight into the types of objects and materials recovered from across England and Wales through metal detecting. Copper and copper alloy artefacts make up the majority of finds recorded by PAS, forming 63% of their current online records (Haldenby and Richards 2010, 1152; British Museum). Copper has been studied extensively in corrosion studies and was intended to form a part of the current study. However, in terms of artefacts from the ploughzone, lead bullets are more suitable due to their standardised manufacture, short usage period, and their permanent presence in the topsoil. Silver is the second most common recorded metal type at 17% of the total PAS data, but is not studied in this research due to its corrosion resistance and nobility.

Iron is well known for being highly prone to corrosion and is often found during excavations and during detecting in very poor condition. Iron often degrades very rapidly and rarely forms protective patinas on its surface, making it vulnerable to deterioration. However, because of the problems surrounding the recovery, treatment and conservation of iron, it requires a lot of time and resources to conserve and study. Though iron has been studied frequently in corrosion research (Gerwin and Baumhauer 2000; Graham and Cox 2001; Wagner *et al.* 1998), it is not an ideal material to establish experiments and condition methodologies on as it corrodes very quickly, its corrosion products are very difficult to identify and it is often found in unidentifiable forms making it difficult to assess an object's overall condition (Graham *et al.* 2007, 48). Furthermore, metal detecting is usually carried out in non-ferrous mode due to the sheer amount of background modern iron in British fields and so many assemblages contain little iron. Only 0.4% of the PAS records are iron objects, reflecting a lack of recovery and recording of iron objects from detecting activities.

Both copper and iron have been studied extensively in previous research in stratified contexts and will not be studied here, though there is great potential for the study of these metals in unstratified contexts in future (Gerwin and Baumhauer 2000; Dillmann, Neff and Feron 2014; Graham and Williams 2008; Graham and Cox 2001; Fjaestad *et al.* 1998; Wagner *et al.* 1998; Madsen, Anderson and Anderson 2004).

Lead has been studied far less in the archaeological record than copper and iron, mainly due to its lack of conservation needs (Cronyn 1990). However, lead is a significant metal in antiquity and is the third most common metal type recorded by PAS, forming 6% of their archive (British Museum). Lead bullets from gunpowder weapons form a key component of battlefield assemblages from the 15th century onwards, and small arms bullets become the main artefact type in assemblages by the early 17th century. Handguns did not replace the longbow as the main weapon of choice until the 16th century, though remains from the Mary Rose shipwreck indicate bows were still in use during the mid 16th century (Ball 2011, 230; Foard, Janaway, and Wilson 2010, 10-11). Over 3,000 artefacts were uncovered from the battlefield of Edgehill during the 2004-7 survey, 34% of which were lead projectiles, indicating that they form a significant part of battlefield studies (Foard 2012, 154).

Lead bullets from battlefield sites have been chosen as the object type to study in this research for the following reasons:

-Bullets can often be dated to the exact day they entered the soil (i.e. the day of conflict) and so the time they have resided in their burial environment is known

-Bullets are used once and therefore most damage will be inflicted after deposition

-They are manufactured in a systematic way using similar equipment and are of similar compositions

-Very little difference exists in forms and shapes and so they are easily identifiable as an object type

-Bullets are plentiful and the most common artefact types retrieved from battlefields so a large dataset can be produced, the results of which are widely applicable to other collections

-Battlefield metal detecting surveys are often systematically carried out and the locations of bullets accurately located using GPS systems so the mapping of artefact condition can be conducted across landscapes (Foard 2012, 154)

Lead bullets are an excellent artefact class on which to undertake a pilot study to develop a methodology for assessing the condition of object types in burial environments. This methodology can then be used as a model on which to build and develop for other site and artefact classes in future investigations.

3.2.1 The study of lead bullets

Lead bullets have been analysed and recorded in great detail, producing datasets on their weight, diameter, projectile type, and surface features, and experimental firing has been carried out to assess impact damage and velocity (Harding 2012, 19; Sivilich 1996, 10; Parkman Unpublished). Other studies have focused on mapping the location of bullets to interpret spatial relationships on how conflict was fought across landscapes (Ferguson 2013b; Foard and Morris 2012). Attempts have also been made to identify the source of lead used for production of projectiles, through analysing lead isotopes in corrosion products (Hall *et al*. 2011; Harkins 2006, 68). Further scientific techniques have recently been used; X-ray Fluorescence (XRF) has been carried out on bullets and case shot in order to identify geo-spatial patterns, the sources of lead used and to identify projectiles from opposing armies based on their composition (Hall *et al*. 2011; Poston Unpublished; Seibert *et al.* 2016; Sivilich and Seibert 2016).

Very little has been studied on the condition or survival of lead bullets in the ground and how this relates to their soil environment and land use history. This is an important area of concern as Foard has commented on the huge variation in the condition of bullets from different sites of conflict in England (Foard 2012, 153). Another area of research which requires investigation is whether the composition of bullets has affected their survival in the ground. It is only recently that researchers have begun to study the composition of lead bullets in depth, linking the sources of material to other lead objects which have been melted down and recycled (Sivilich 2016; Sivilich and Seibert 2016).

Analysing the shape and surface details of artefacts can reveal a great deal about the life history of objects. Lead bullets are diagnostic objects for battlefield studies and analysis can reveal how the object was manufactured, its transportation history, how it was loaded and fired, whether it impacted on a target, and its history in the ground (Foard 2012, 94; Harding 2012, 44). Details can reveal aspects of the battle; the diameter of bullets can reveal what type of weapon was used in battle, impact marks can identify target areas, and concentrations of bullets with human tooth marks may indicate the locations of where surgery was carried out on the battlefield (Sivilich 1996, 105; 2009, 94).

3.2.2 Loss of data from lead bullets

The amount of data that can be retrieved from artefacts depends upon their level of preservation and their spatial context. Much information is lost between deposition and recovery of artefacts, and it is this loss which gives artefacts value; the threat of loss gives incentive to preserve and protect, and assessing the amount of data still available in these objects is key to establishing their archaeological value (Caple 2000, 29). Our understanding and interpretation of objects is inevitably biased towards what data survives in the ground and by what archaeologists have been able to recover during excavations and surveys.

Metal objects will start to decay almost immediately after their manufacture. During transportation to and around the battlefield before deposition in the ploughzone, bullets may have rubbed together in barrels or in bullet pouches, resulting in abrasion wearing down the characteristic features on the surface (Foard 2012, 101; Sivilich 1996, 107). Once in the ground, corrosive processes will affect the quality of visible surface details on bullets, either by obscuring or physically damaging features.

The main factors which contribute to the overall condition of buried metallic archaeological artefacts are:

-Metallic composition and crystallographic structure

-Manufacturing process

-Use of object during its lifetime

-Date of object

-Condition of object when it entered the ground

-Period of time in the ground

-Soil chemistry

-Disturbance and taphonomic/diagenetic processes (land use, contamination, animal and human activity)

Decay over time is inevitable, but it leads to a loss of information the objects can provide on their function, use and manufacture (Neff *et al*. 2004; 739). The UK contains countless numbers of artefacts still buried under the ground, with a staggering 14 million estimated to be lost through corrosion each year (Rimmer and Caple 2008, 10). At some stage an artefact will no longer be of archaeological value because it has deteriorated so severely (Kibblewhite, Toth, and Hermann 2015, 252). To be able to manage and attempt to prevent artefact loss through decay in the ground, the process of their decay needs to be understood and their condition needs to be addressed in order to understand how and why they are deteriorating and whether their condition is stable or unstable (Dillmann, Neff, and Feron 2014, 568). This knowledge will also help in identifying when materials are likely to be in good or poor condition on sites and help to prioritise conservation and investigation.

Corrosion makes the analysis of surface marks difficult to distinguish (Foard and Morris 2012, 150). Corrosion may affect the accuracy of bore measurements, making analysis of bullet size misleading. Adhered corrosion products may also change the mass of bullets, though this is rare and loss of weight by corrosion is only likely to result in up to 3% loss in weight (Harding 2012, 80). Post depositional damage may also occur from impact with ploughshares on arable fields, though it is difficult to distinguish between post depositional impacts and damage inflicted during the lifetime of the bullet (Foard and Morris 2012, 150). Harkins also notes pitting on a bullet from the site of Edgehill as a result of the gun powder not fully burning, leading to scarring on the lead, though this type of scarring is again difficult to identify (Harkins 2006, 42).

When determining the condition of an object, it is important to consider any potential post collection damage. Depending on how the objects have been handled and stored, objects may have suffered abrasion damage when stored as bulk finds, and may continue to corrode if storage materials promote corrosion or the relative humidity is too high. This is a particular concern for the Wareham collection which has almost certainly suffered post recovery damage (see chapter 7).

3.2.3 Identifiable surface details on bullets

It is important to be able to identify marks on the surface of bullets to understand how much archaeological data has survived the burial period. The ability to identify surface marks on bullets has formed a significant part of the condition assessment methodology applied in this research (see section 3.4 and appendix I).

Evidence which needs to be identified on bullets include manufacturing marks including mould seams, sprues and excess flashing from lead seepage (figure 9) (Harding 2012, 45; Sivilich 2009, 85; 2016, 16). Other marks may include concentric rings or striations left from the interior of a mould (figure 10). Wavy wrinkles on the bullet surface may be apparent if the molten lead was not hot enough when poured into the mould, resulting in cooling lines on the surface (Harding 2012, 46).

Loading and firing marks may also be visible. Bullets may suffer surface damage from being rammed into the gun or if wadding is not sufficient in the barrel (Harding 2012, 48). *Banding* may survive on the surface if, during firing, pressure builds up behind the bullet, flattening the ductile lead into a different shape (figure 11) (Harding 2012, 49). This may occur particularly if the bullet was a tight fit in the gun barrel. The calibre of musket barrels in guns was standardised by the early 17th century, but the diameter of bullets could still be quite variable (Campbell and Mills 1977, 554). Bullets may also suffer gas erosion as fumes in the bore escapes during firing, disfiguring the lead. However, this evidence is extremely difficult to identify and is often overlooked, having been obscured or lost due to post depositional corrosion or abrasion of the surface (Harding 2012, 57).

Impact damage is regarded as a significant aspect of bullet surface evidence. Lead bullets are soft and take on a variety of different shapes on impact and so analysing impact marks can help identify what, if anything, a bullet hit on its journey through the air (Harding 2012, 74; Sivilich 2009, 89). Marks can vary from slight disfigurement on impact (figure 12), whilst others may be reduced to a flattened disc if impacted on stonework or lodged into a tree (Sivilich 2016, 53). It is rare to find evidence of bullets hitting human targets, though a number of bullets have been found embedded in bone at the Battle of Waterloo (Sivilich 2016, 57-58). It is important to note that lack of impact damage does not indicate lack of use, as many bullets which have been fired lack any evidence of surface damage. Harding showed that bullets can be fired, hit the ground and suffer no impact damage (Harding 2012, 74). Parkman has carried out firing experiments on fresh cast bullets in order to replicate impact marks on archaeological bullets. This will enable identification of typical marks created by impact on wood, stone and other surfaces on the battlefield (Parkman Unpublished).

Bullets may also retain surface marks from activities after their firing. Assemblages including Easton Maudit in Northamptonshire, and Edgehill in Warwickshire show signs of being chewed. Chewing marks include those made by humans during conflict, and those made by animals on agricultural land years after the conflict took place (figure 13). Humans may have chewed bullets in battle for a number of reasons; to combat thirst in hot weather, to hold the bullet whilst preparing the gun for loading, to adjust the shape of an oversized bullet to fit down the bore, to encourage infection in the proposed target, or to have something to bite down on during battlefield surgery; hence to 'bite the bullet' (Foard 2012, 103; Harding 2012, 78). The memoirs of General John Stark note that he would have ‘died of thirst’ if he had not had a bullet to chew on (Stark and Stark 1860, 67).

Surface details, alongside location data and dimensions, are the most valuable details retained by bullets and give them their archaeological value. The quality of this detail will determine how much data researchers can obtain from them. Identifying pre-depositional from post-depositional markings is difficult, but important in order to understand how much damage bullets have suffered during their use, as well as damage suffered during its time in the ground. As lead is a soft metal it can easily be marked or distorted. The degree of decay by biological, chemical and physical factors in the soil will determine the usefulness of bullets as archaeological objects (Caple 2006, 192; Foard 2012, 51).

Figure 9: Lead bullet with a mould seam with excess flashing and sprue attached (MOR 0016).

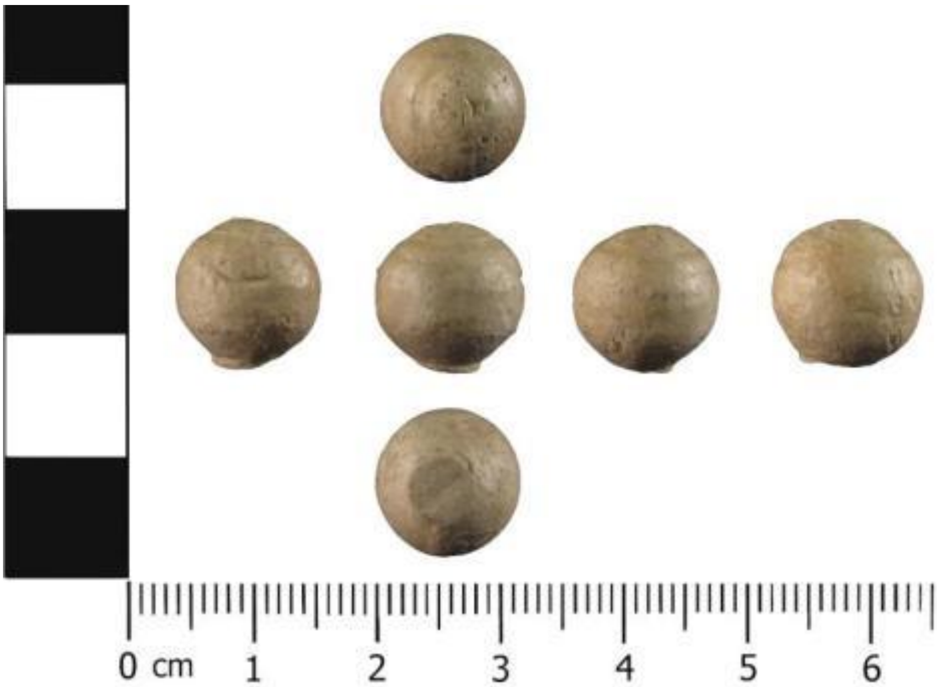


Figure 10: Lead bullet with striations from interior of mould (MOR 0140).

Figure 11: Lead bullet with banded flattened area around circumference where the bullet has been forced against the sides of the gun bore (EDG 2141).

Figure 12: Lead bullet with a disfigured dented edge due to impact (EDG 2231). .

Figure 13: Lead bullet with chewing marks from a farm animal (EDG 749). .

3.3 Lead corrosion

In order to devise a systematic condition assessment of lead bullets, a detailed understanding of the corrosion process of lead and its history as an archaeological material needs to be addressed.

3.3.1 Extraction and purity

Lead is likely to have been one of the first metals to be smelted, having been in use for at least 6,000 years (Costa and Urban 2005, 48; Tylecote 1983, 389). It became common in the archaeological record in the Roman period and was extensively used in Graeco-Roman plumbing, known in Latin as *plumbum* meaning 'liquid silver' (Sease 1987, 82-83).

Lead has a low melting point and can be easily cast and alloyed (Costa and Urban 2005, 48; Schindelholz 2001, 22). Lead is extracted from its ore galena, a lead sulphide (PbS)), which usually contains approximately 80% lead (Stos-Gale 1985, 4; Craddock 1995). The purity of lead can differ depending on the ore extraction process and the impurities present in the ore itself. It often contains traces of silver, but may contain antimony, arsenic, iron, cobalt, nickel, zinc, sulphur or chlorine (Cronyn 1990, 202; Schindelholz 2001, 22; Craddock 1995, 206).

Lead is easy to manipulate, meaning it is often recycled and reprocessed, increasing the likelihood of further impurities. It has been suggested that up to 10% of lead in use today dates from the Roman period (Walker and Hildred 2000, 220). It is therefore likely that the majority of artefacts are made from impure lead and the purest leads were restricted to high quality objects (Costa and Urban 2005, 49; Mattias, Maura, and Rinaldi 1984, 88). Items only to be used once, such as lead bullets, may have been made from inferior or recycled lead (Walker and Hildred 2000, 220). However, analysis in this study has shown that the majority of lead bullets from this project are relatively pure (see chapters 5-7).

The term 'pure' is misleading in that all lead contains some impurities (Costa and Urban 2005, 50). Studies have shown early modern bullets to contain traces of silver, tin, antimony and arsenic (Seibert *et al*. 2016, 145; Scott, Thiessen and Dasovich 2014, 80). Some have suggested that purity may contribute to the survivability of the metal. However, it should not be assumed that the purer the lead the more resistant to corrosion the object will be, particularly when acetic acid is present, as almost pure lead is more prone to acid corrosion (Tetreault, Sirois, and Stamatopoulou 1998, 26; Tylecote 1983, 400). Research has suggested that traces of iron, zinc or antimony will increase corrosion in lead, whereas traces of tin, copper, silver and gold will improve the resistance of lead to corrosion (Costa and Urban 2005, 52). Though on its own lead metal is considered to be corrosion resistant, when alloyed with other metals such as copper it can lead to dispersion of metal globules in the metallic structure, weakening the mechanical properties of the metal (Fernandes, Van Os and Huisman 2013, 5; Craddock *et al*. 1985). The composition of a sample of lead bullets will be examined for each case study in this research in order to develop further insight into the implications on lead purity and the preservation of bullets. Obtaining this data will enable a better understanding of the effects impurities may have on the decay process.

As soon as a metal is separated from its ore and formed into an object, it is less stable. The decay process begins almost immediately as the metal attempts to revert back to its natural state (Selwyn 2004, 6). With the exception of very stable and noble metals like gold and platinum, metals react with their surrounding environment to form more stable compounds. This creates a chemical change in the metal through a process known as corrosion (Cronyn 1990, 165)

3.3.2 Corrosion process

Corrosion is an electrochemical reaction between an electrically conductive material (metal) and its environment (water/water vapour) which results in the deterioration of the substance (McNeil and Selwyn 2001, 605; Corcoran *et al*. 1977, 473).. A flow of electrons occurs within the metal and a flow of ions occurs in the surrounding solution which acts as an electrolyte (Turgoose 1985, 16). Corrosion occurs at the metal-solution interface so long as the corrosion cell consists of the following:

-Anode (positive electrode where oxidation takes place)

-Cathode (negative electrode where reduction takes place)

-An electrolyte (for flow of ions to take place)

-Electrical connection/pathway between the anode and cathode (to allow flow of electrons)

If all these elements are in place an electrochemical cell will form between the metal and its surroundings (figure 14). Corrosion will take place in the presence of air and water. Water acts as the electrolyte and oxygen in the air acts as an electron acceptor. Metal is lost at the anode and ions and electrons enter the solution through a process of oxidation, for example in the oxidation of iron:

$$Oxidation = Fe \longrightarrow Fe^{2+} + 2e^{-}$$

Oxidation forms positive metal ions which enter the solution and, if they are soluble, will diffuse away from the surface of the metal, but if they are insoluble, they will precipitate onto the surface of the metal (Selwyn 2004, 20). If ions are soluble and diffuse away then the metal is lost, ions continue to be lost from the surface and the metal continues to corrode. This occurs in extreme environments of very low or high pH where insoluble corrosion products are not formed.

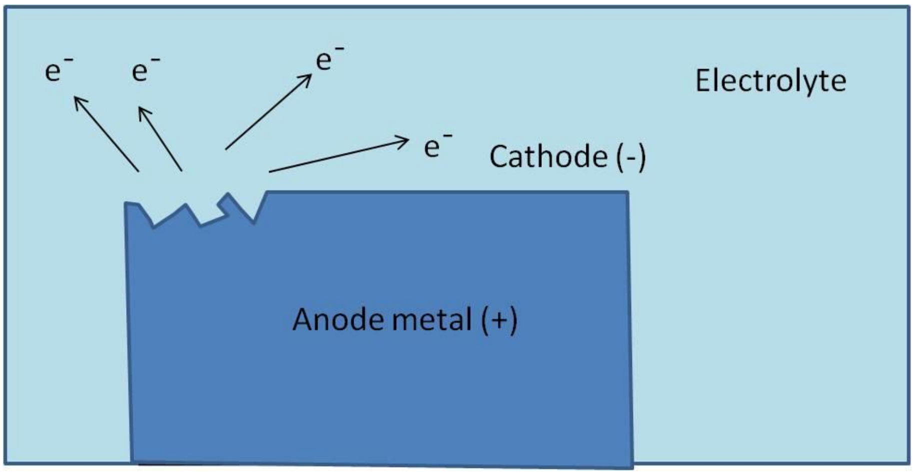


Figure 14: Diagram of a corrosion cell showing the site of corrosion on the anodic metal and the loss of electrons through oxidation.

The cathodic site accepts released electrons from the anode through reduction and in most cases the metal ions will react with negatively charged anions in the surrounding solution to form new corrosion products on the surface of the metal (Cronyn 1990, 168) (figure 15). Negatively charged anions are normally readily available in the surrounding environment; in soils this is generally oxides, hydroxides, sulphates, carbonates and chlorides. When these insoluble corrosion products form on the surface of the metals, it restricts access for oxygen and water to react with the underlying metal and corrosion rate is reduced, or in some cases stopped entirely; this is known as passivation (Cronyn 1990, 168). As the corrosion process continues, corrosion cells will form on the surface of the metal. This can create a uniform surface layer, or patina. However, impurities in the metal surface or areas of stress or cracks in the metal can accelerate corrosion (Selwyn 2004, 21).

Corrosion can take many forms (figure 16). Lead generally turns a dullish to whitish grey as it corrodes (Mattias, Maura, and Rinaldi 1984, 87; Sease 1987, 82). Lead is regarded as corrosion resistant only due to its initial corrosion process (Tranter 1976, 222). In most aerobic moist soils, lead will react to form a lead oxide. It further reacts with CO_2 to form basic lead carbonate (cerussite), which is the most common product found on lead artefacts (table 11) (Tetreault, Sirois, and Stamatopoulou 1998, 25; Black and Allen 1999). This uniform corrosion layer, or *patina,* tends to be adherent, insoluble, electrically passive, hard, and will not oxidise in air and therefore forms a protective barrier restricting oxygen and other elements to the underlying metal (Costa and Urban 2005, 50; Rimmer *et al.* 2013; Rodgers 2004). Lead patinas are usually 'stable' in that the metal now has a limited corrosion rate (Turgoose 1985, 15).

However, in some environments such as very acidic waters, this initial patina does not form. Soluble corrosion products are formed and the metal will rapidly deteriorate. This is why, in some environments, lack of archaeological evidence does not indicate lack of human activity, but lack of material survival. Furthermore, the patina on lead may not form a truly passive layer and some corrosion may still occur, particularly if lead is put under stress (Edwards 1996, 89). Localised corrosion develops as a secondary form of corrosion after uniform corrosion, leading to pitting, cracks and perforation on the metal surface causing penetrable damage (Tetreault, Sirois, and Stamatopoulou 1998, 27).

If lead corrosion is not stable and solid stable compounds have not formed a layer on the surface, non-protective soluble powdery products will form (Schindelholz 2001, 220). The solubility of compounds is essential to the preservation or decay of lead. Carbonates, oxides and sulphates are generally insoluble passive compounds, whereas chlorides, nitrates and caboxylates are soluble and will not aid the preservation of lead.

Corrosion by *erosion* is common when the electrolyte/soil solution flows rapidly, physically wearing down the surface of the metal, removing passive layers and exposing the metal underneath. This is one of the reasons why free draining soils can be particularly dangerous for the preservation of metal as water flows through the soil column at a faster rate (Kibblewhite, Toth, and Hermann 2015, 251). The relationship between abrasive metal surfaces and the soil type will be examined in this study to assess any correlation between soil texture and the effects of abrasion on bullet surfaces.

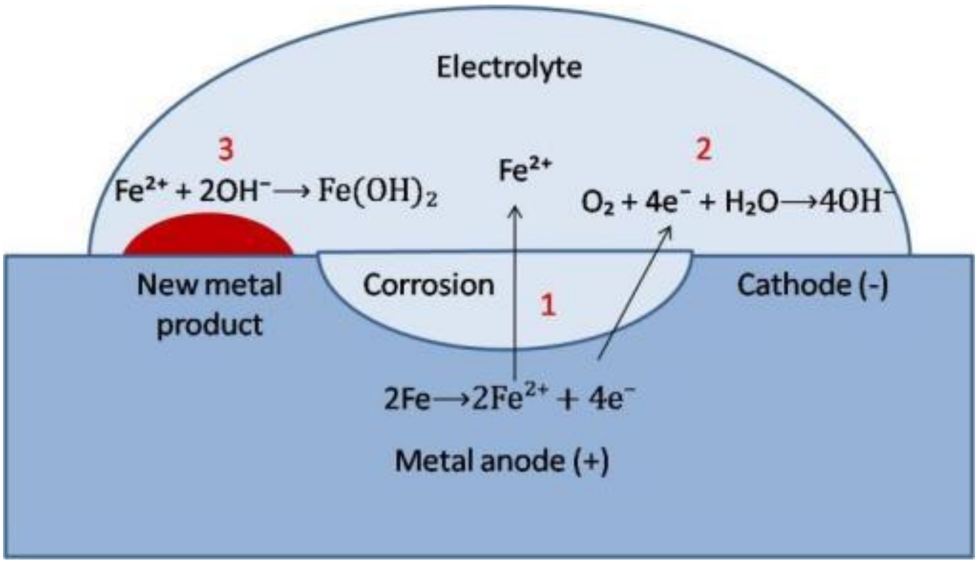


Figure 15: Electrochemical cell showing the process of corrosion: 1. a loss of metal ions from the metal anodic site, metal ions enter solution 2. cathode gains electrons from anode and reacts with oxygen in the air/solution to form hydroxide 3. metal ions in solution and the formed hydroxide at the cathode or other anions in solution react to form new metallic compounds on the surface of the metal. Adapted from Cronyn (1990).

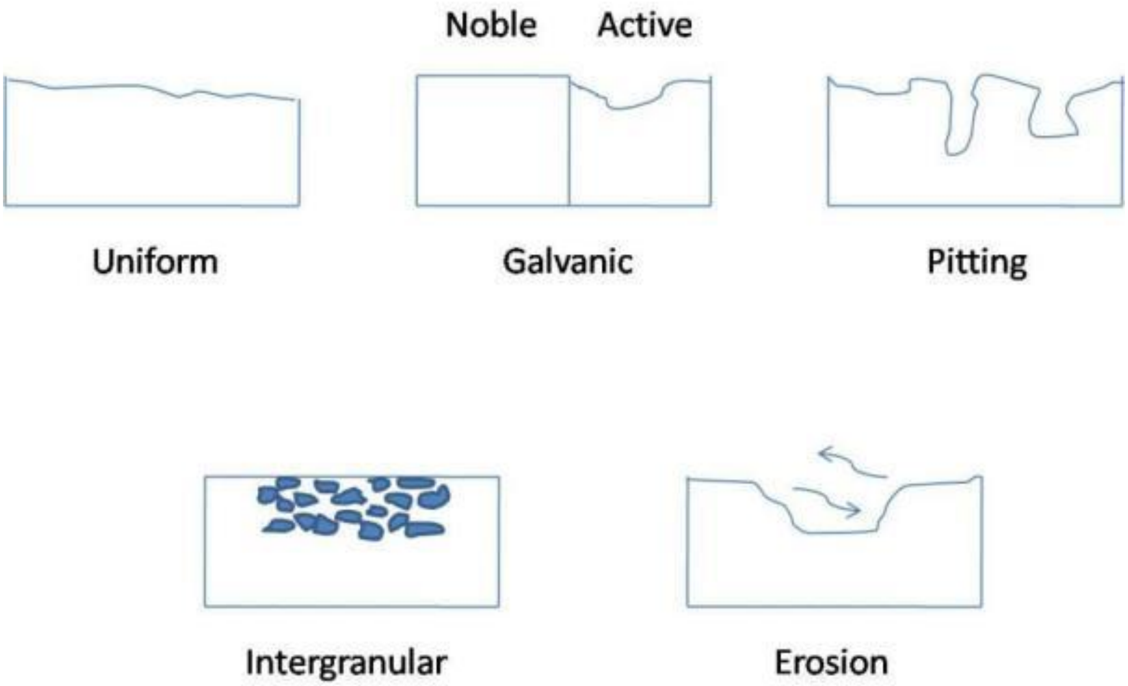


Figure 16: Most common forms of corrosion found on buried metals. Adapted from Jones (1996, 10).

Corrosion product	Products and formulae	Colour	When they form
Lead (II) oxide	Litharge (PbOα) Massicot (PbOβ)	Dull or shiny brown	Aerobic environments
Lead (II) carbonate	Cerussite ($PbCO_3$) Hydrocerussite ($Pb_3(CO_3)_2(OH)_2$)	Greyish white to white	Neutral to alkaline environments in presence of carbon or CO_2
Lead (II) sulphide	Galena (PbS)	Black	Anaerobic in presence of sulphate reducing bacteria or polluted urban environments
Lead (II) chloride	Laurionite (Pb(OH)Cl) Chloropyromorphite ($Pb_5(PO_4)_3(Cl)$)	White, powdery	Marine, burnt and contaminated environments

Table 11: Common corrosion products formed on buried archaeological lead. Adapted from Campbell and Mills (1977), Tylecote (1983, 400), Turgoose (1985), Cronyn (1990), Davis, Hunter and Livingstone (1995), Schindelholz (2001).

3.3.3 Corrosion rate

Experiments on simulating lead corrosion have shown that patination is usually formed in the first four weeks of atmospheric exposure (Black and Allen 1999, 197). Once this layer is formed, corrosion slows as the accessibility for reactants to the metal surface is reduced (Tranter 1976, 224). This indicates that the initial exposure to an environment is crucial for lead to form a protective barrier. If its initial environment does not allow patination to form, in acidic waters for instance, then the metal will corrode indefinitely.

When an electrochemical cell has been established, this contains an electrochemical potential (eH). When this potential is high, the more likely oxidation and reduction is to take place (Cronyn 1990, 168). Water creates the most common and effective electrolyte; damp soils and high humidity (>65% RH) work best in maintaining a source of water at the metal-solution interface (Selwyn 2004, 21). The higher the conductivity of the electrolyte, the faster the corrosion rate will be as the potential for ion flow increases. Conductivity is increased by the presence of salts and pollutants such as in seawater or polluted urban environments. The act of adding salts to soils in the form of applying fertilisers to fields or adding salts to roads which subsequently leach into the ground can increase conductivity and ultimately increase corrosion rates (Nord, Mattsson, and Troneer 2005).

Access to oxygen will also affect corrosion rates. Oxygen will tend to form solid corrosion products on metal surfaces. However, when there is plenty of hydrogen or hydroxyl ions in solution, as is the case in very acidic or very alkaline soils, these will accept electrons more readily than oxygen and reduction will occur very rapidly. Reacting with hydrogen or hydroxyl will form soluble metal products which diffuse away from the object, failing to form solid metal products on the surface of the object. This is why in very acidic (plenty of H^+ ions) or extreme alkaline (plenty of OH^-) conditions, corrosion of metals can take place very rapidly as solid corrosion layers are not formed and metal ions are free to diffuse into solution. This reaction and its likelihood depend on the metal's reactivity (figure 17) and its electrode potential. Iron is very base, has a high electrode potential and easily reacts with hydroxyl ions which is one of the reasons why iron corrodes very rapidly (Selwyn 2004, 22).

Figure 17: Main archaeological metals in order of reactivity. The more base, the more reactive a metal is. Adapted from Cronyn (1990).

3.3.4 Corrosion states

Marcel Pourbaix developed the 'Pourbaix diagram' which maps out possible stable phases of an electrochemical system in an aqueous solution, depending on a system's pH and Eh. It maps out when different metals are likely to be active, passive or immune to corrosion and what products are likely to form depending on the environment (figure 18). An *active* state means the metal is reacting with its environment and is actively corroding with a continuing loss of metal from the objects (Logan 2007, 1; Schotte and Adriaens 2006, 297). When a metal remains unchanged for an indefinite period after forming stable corrosion products on its surface it is known as *passive* (Turgoose 1985, 18). When a metal fails to react with the electrolyte and does not corrode it is known as *immune*. Immunity is uncommon, though platinum and gold are very resistant to corrosion and may be immune due their nobility. Immune metals are stable (Selwyn 2004, 24).

However, Pourbaix diagrams only give a basic predictability for corrosion and the concept of passivation in an archaeological context has little application when the object is beneath the ground in a changing environment for hundreds, if not thousands of years (Turgoose 1985, 18-21). The diagrams simulate what happens to a given metal in a pure water environment, but natural environments do not contain pure water; many other factors influence the stability of the metal such as oxygen content, carbon dioxide content, conductivity, salts present, microorganisms, and temperature. The diagram predicts that lead carbonate for instance will only form in solutions with a pH of 9 or higher. However, experiments by Woodruff showed that lead carbonates can form on lead bullets at a pH of 6 and a voltage of -0.49V which is predicted as being immune according to the Pourbaix diagram (Woodruff 2015, 31-32). Therefore, the diagrams should be used to predict corrosion states with caution.

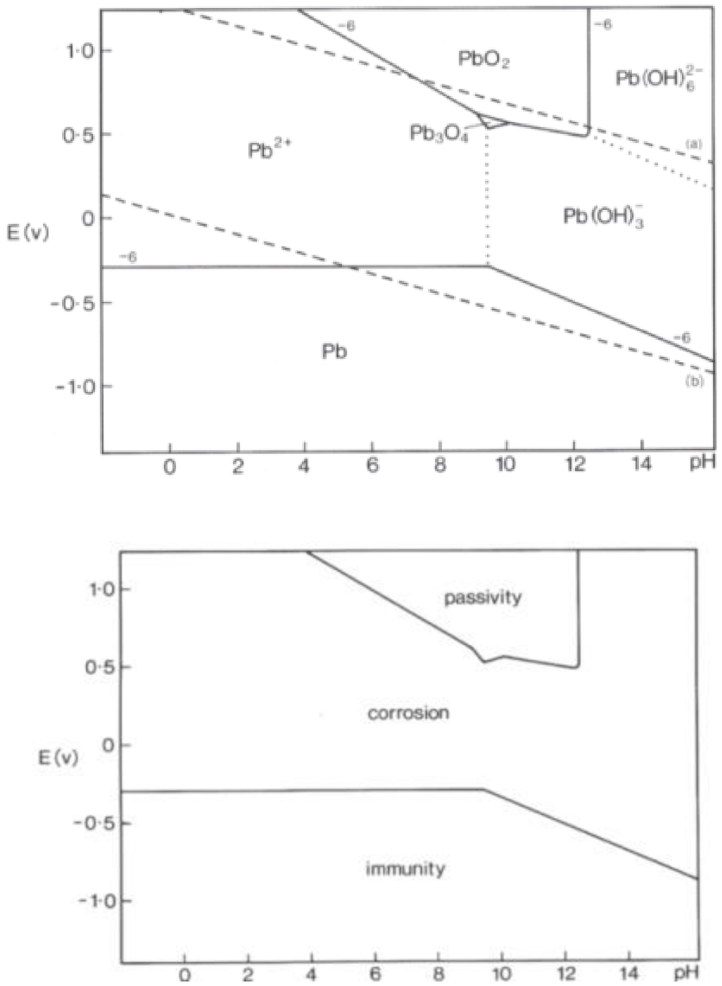


Figure 18: Pourbaix diagram for a lead water system (Turgoose 1985, 22). Note that when Pb(OH) is predicted to form, an oxide or carbonate will form. This diagram reveals that in order for lead to be immune to corrosion the redox potential has been be negative which will not occur in aerated soils. In the majority of situations some form of corrosion will take place.

3.3.5 Active corrosion

Common signs of actively corroding lead are powdery surface residues, severe cracking (figure 19), erosion of the surface, flaking and denting. Lead is particularly prone to cracking and flaking as it can become brittle when dried (Rimmer *et al.* 2013, 12-13; Schindelholz 2001, 22; Sease 1987, 82-83; Watkinson and Neal 1987, 45; Garcia, Gilroy and Macleod 1998, 124). The process of active lead corrosion was proposed by Turgoose (1985) and later visualised by Degrigny and LeGall (1999) (figure 20), and is most commonly understood in a post excavation environment. When lead is exposed to acetic acids, corrosion can accelerate and any protective patina may fail to defend against attack. Acid vapour condenses and dissolves on the surface of the metal, allowing acetate ions to interact with lead compounds. Lead acetate stimulates the dissolution of lead carbonates, corroding protective films on lead objects. New corrosion products formed can force the original patina layers away, forming cracks and fragmentation of the surface. This cycle of corrosion by acids continues to attack the metal over time which is why it is particularly important to maintain relative humidity (RH) levels when storing lead artefacts and to keep them away from acid sources; RH should be <40% for the storage of lead (Allen and Black 2000, 42; Degrigny and Le Gall 1999, 158; Schotte and Adriaens 2006, 297-298; Tetreault, Sirois, and Stamatopoulou 1998, 24).

Patinas can also be broken down, leading to further active corrosion. Abrasion and compaction in the ground can expose underlying metal, which acts as a local anode in relation to the oxide/carbonate patina which becomes cathodic. This reaction initiates growth of stress corrosion cracking leading to mechanical rupture of the artefacts (Edwards 1996, 91) (figure 21). This process is a potential issue in the ploughsoil as the soil is churned, moved and compacted through cultivation processes making metals vulnerable to abrasion and patina breakdown, initiating new corrosion reactions which may be rapid, particularly in acid environments.

Figure 19: Evidence of severe cracking on the surface of a bullet from the siege of Wareham (WAR 2219). .

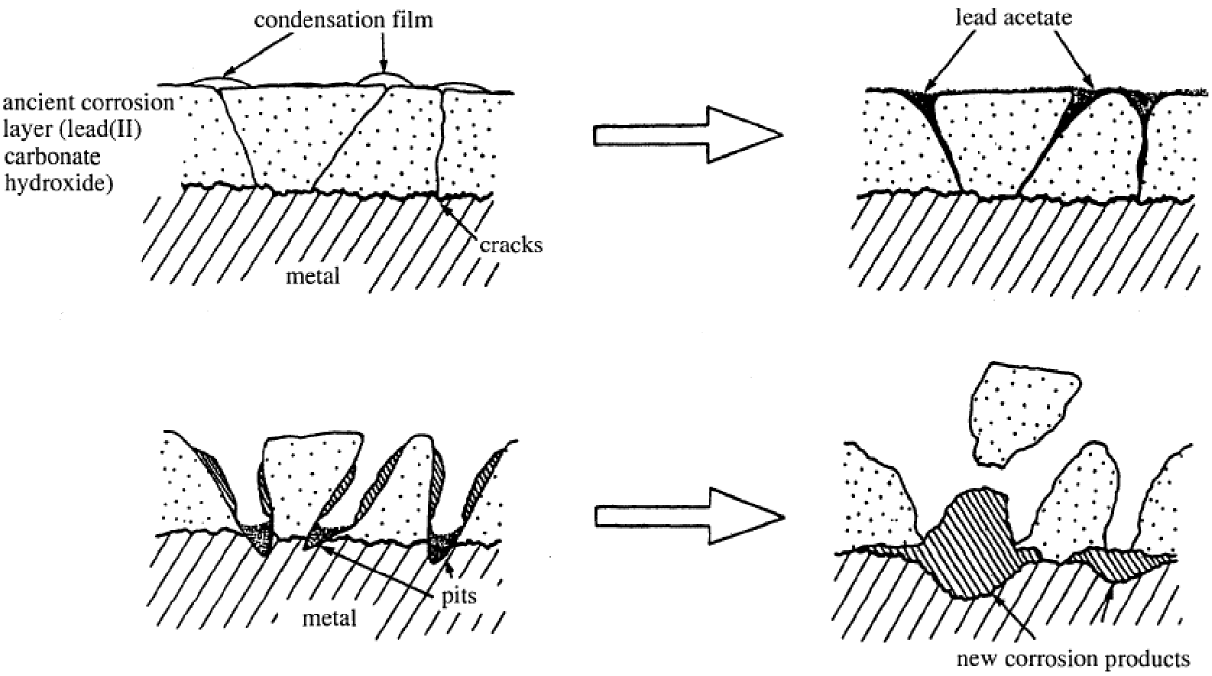


Figure 20: Active corrosion on lead showing how lead acetate forces the fragmentation of lead. Proposed by Turgoose (1985) and visualised by Degrigny and Le Gall (1999, 158).

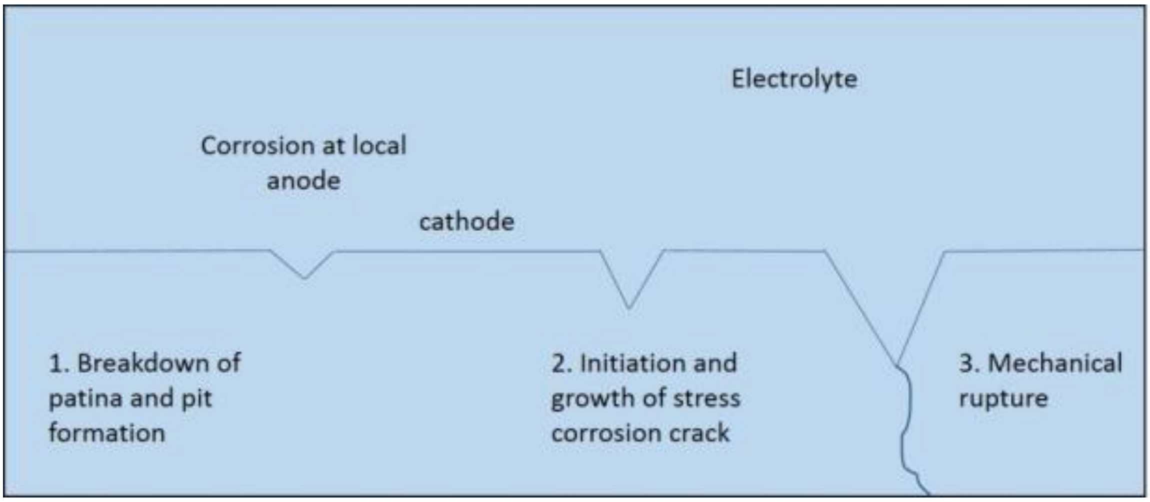


Figure 21: Breakdown of surface patina and formation of stress corrosion cracking on metal. Adapted from Edwards (1996, 91).

3.3.6 Effect of pH

In general, protective passive layers of corrosion will form on lead in an environmental pH threshold of 6-10. Ideal levels are considered to be pH 6-8.5 for lead preservation. However, in extreme pH (>11 or <5.5) the potential for these layers to dissolve will be higher (Costa and Urban 2005, 50; Goodwin 2006, 771). Gilbert observed that in conditions of pH 4.5 or below, lead with corrode at an accelerated rate (Gilbert 1946, 171). In acidic solutions plenty of hydrogen ions are available and in alkaline solutions plenty of hydroxyl ions are available and these will accept electrons during oxidation and reduction instead of oxygen. These form of bonds form soluble compounds that diffuse away from the artefact without forming a protective barrier.

Standard corrosion reaction:

$$Oxidation = Fe \longrightarrow Fe^{2+} + 2e^{-}$$

In acidic conditions the reduction reaction involves hydrogen ions:

$$2H^{+} + 2e^{-} \longrightarrow H_2$$

Lead can corrode very quickly in acidic wet environments. If lead objects are initially deposited in this environment, it is likely they will corrode so rapidly that they will not survive in the archaeological record (Cronyn 1990, 204). As Black and Allen have shown (1999, 197), patination on bullets usually occurs in the first four weeks of atmospheric exposure, but if the initial environment is very acidic, the metal may effectively dissolve. An assessment of the Lafelt battlefield included bullets found within mass graves on the site. Bullets found alongside bodies were found to exhibit a higher degree of corrosion compared to bullets found in other parts of the battlefield. It was suggested that the high level of corrosion was a direct result of acids generated by the decay of bodies in the graves (Foard Unpublished,-a). This suggests the decomposition of bodies on battlefields could affect the early stages of corrosion of artefacts. This theory is worth further investigation, but is outside the scope of this current project.

The dissolution rate of lead compounds increases significantly in acidic waters (figure 22) (Black and Allen 1999, 195; Turgoose 1985, 21); nitric and acetic acids are particularly harmful to lead (King *et al*. 2000, 41). Nitrates can become nitric acid when in solution which is why adding nitrates to soil can be particularly damaging to metal artefacts (Sivilich 2016, p 119).

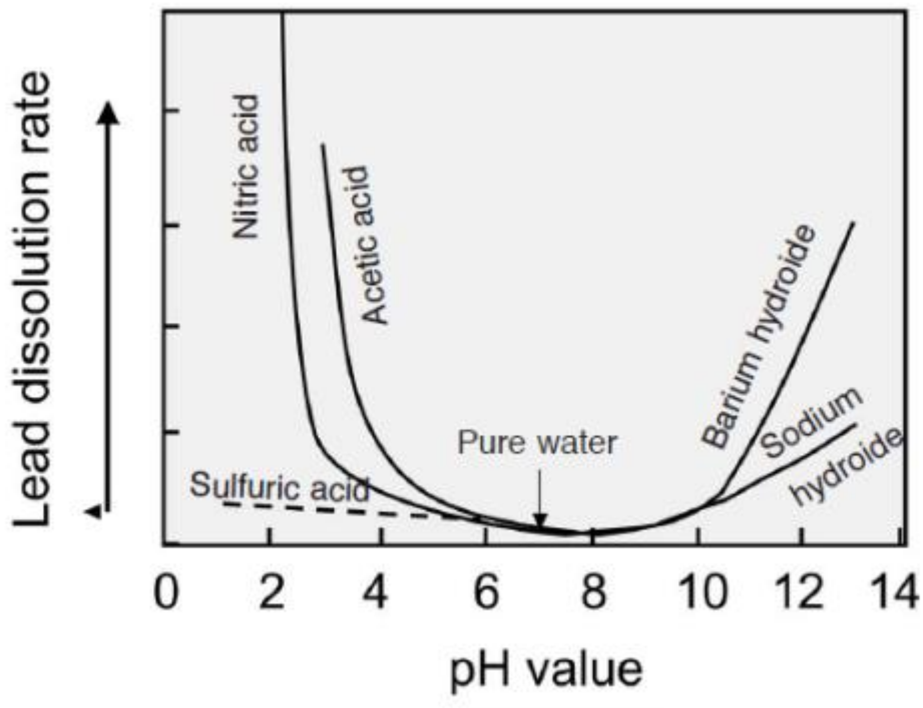


Figure 22: The effect of pH and acids on the dissolution rate of lead (Costa and Urban 2005, 50).

3.3.7 Lead-tin alloys

During composition analysis of the bullets in this study, it was revealed that 98.73% of all bullets analysed also contained the metal tin (see section 8.3). It is important to address how the corrosion of tin varies from lead and the possible effects this has on the preservation of lead tin-alloy bullets.

Lead and tin have similarities in their physical and chemical properties; they are both soft metals with low melting points (327°C and 232°C respectively) (Selwyn 2004, 115,141), possess good resistance to corrosion, mainly form similar white corrosion products and are commonly alloyed with one another (Turgoose 1985, 15; Watkinson and Neal 1987, 44). Sivilich states that tin is the most common and logical metal to alloy with lead due to their similar properties (Sivilich 2016, 116). For both lead and tin, initial anodic products formed through the corrosion process are 2^+ cations with similar standard electrode potentials (-0.126V for lead, -0.136V for tin) which means the thermodynamic tendency for the metals to corrode is very similar (Turgoose 1985, 16).

In most conditions tin forms a thin protective oxide film on its surface which is resistant to decay (Cronyn 1990, 211; Selwyn 2004, 123). However, it is unusual to recover non-alloyed tin from archaeological contexts. Metallic tin is only stable above 13°C; when it drops below this temperature βSn is converted to αSn, a dark powder; this is known as 'tin pest' (Van Os, Huisman, and Meijers 2009, 125). Tin is often used in alloys rather than non-alloyed (Historic England 2015a, 56) and it may be that the early use of pewter was due to the realisation that adding lead would inhibit tin pest/disease (Tylecote 1962, 70).

In the majority of environments tin is predicted to be passive which, although not thermodynamically stable, will remain visibly unchanged for an indefinite period (Turgoose 1985, 18; Hoar 1976). The most common product formed on tin is tin (IV) oxide SnO_2 (cassiterite), and for lead the most common product formed is Pb II carbonate compounds (cerussite). This makes both metals resistant to corrosion through the act of passivation.

Lead has always been economically cheaper to produce than tin, especially as the major deposits of tin ores are restricted to Devon and Cornwall in England (Tylecote 1962, 63). One of the most likely reasons for tin being present in lead bullets is the recycling of metals when lead was in short supply. Sivilich states that pewter items may have been melted down and blended with lead in small quantities so as to not greatly change the characteristics of lead bullets (Sivilich 2016, 117). Tin also looks similar to lead and may have been incorporated into objects accidentally when creating lead objects (Tylecote 1962, 69). In terms of the production of lead bullets during the Civil War, the majority of the ore was smelted in lead-producing factories in Derbyshire, Durham, Northumberland and the Yorkshire Dales, and the casting of bullets could be done almost anywhere by contractors and soldiers (Edwards 2000, 102). Both the Royalists and Parliamentarians had issues with accessing enough raw materials to meet demands. Major field armies, such as those which fought at Edgehill, were typically supplied with bullets on a large scale by commercial producers. In times of shortage, roofs and lead guttering were targeted; during the siege of Gloucester in 1643 the 'Vineyard' at Over was stripped of lead, and on a separate occasion at Worcester the cathedral roof was stripped to make bullets in haste (Edwards 2000, 104-105). Hence it is not always apparent by what means lead for bullets has been sourced and cast. Moreton Corbet and Wareham are both siege sites and as local-based battles involving just a few hundred troops, armies may have had to produce their own ammunition, as was the case at the garrison of Gloucester (Howes 1992). This may account for slightly higher tin contents in bullets observed at these two sites as local forces often had to find their own metal sources (see chapters 5 and 7).

3.3.8 Bimetallic corrosion of lead and tin

When lead and tin are melted together and cooled, the solid created consists of two phases; one that is rich in tin and one that is rich in lead. Alloys that are rich in lead are generally more susceptible to corrosion than tin-rich alloys (Selwyn 2004, 116).

Galvanic corrosion occurs when two metals with different electrode potentials are in contact whilst in an electrolyte. A current will subsequently flow from the anode to the cathode which increases the corrosion at the anode site; generally corrosion rate is higher in alloys than in non-alloys (National Physical Laboratory 1982, 1). Tin is anodic to lead in the galvanic series and slightly less energy is required for it to corrode (figure 23), which means alloying them will result in tin corroding at a faster rate. However, as they have very similar standard electrode potentials (-0.126V for lead, -0.136V for tin), this increased corrosion effect may only be slight. If lead was alloyed with iron for instance, which has a standard electrode potential of -0.447V (Fe^{2+}) (Selwyn 2004, 23), then the iron would corrode significantly faster than lead as there is a greater difference between the electrode potentials of the two metals.

The amount of bimetallic corrosion to occur is dependent on the size of the anode and cathode areas on the metal surface; this is based on the 'catchment area principle'. The larger the cathode compared to the anode, the more oxygen reduction can occur and therefore the greater the galvanic current (figure 24). This means that in theory, the more lead that is alloyed with tin, the greater rate at which the tin will corrode (National Physical Laboratory 1982, 6). Though tin should be slightly anodic to lead, in reality this does not always occur. It is also possible that the acidic conditions produced during the corrosion of tin increase the solubility of lead compounds such as cerussite which would lead to a breakdown of lead compounds, which may account for the breakdown of the patina on some bullets at Wareham (chapter 7) (Turgoose 1985, 24).

It is possible that an increase in tin content in lead bullets may increase the corrosion rate of lead-alloy bullets. The more lead present in an alloy, the increased risk of corrosion, as the larger the cathode region is, the more oxygen reduction can occur and the greater galvanic current to the tin anode (figure 25). However, as the electrode potentials of lead and tin are very similar, this increased risk of corrosion may only be slight. Sivilich states that lead-tin alloys are vulnerable to corrosion in acidic environments, suggesting that lead-tin alloys in acidic soils will be the worst preserved (Sivilich 2016, 118). Three lead bullets from the battlefield of Pinkie in Scotland were analysed using XRF, revealing the bullet with the highest level of corrosion was composed primarily of tin (Foard and Morris 2012, 153; Foard 2008b). Two bullets with a composition of 52-84% tin and 69-88% tin showed signs of deep penetrating corrosion, whilst the third bullet which had a composition of 71-97% lead only showed superficial surface corrosion. It was concluded from this data that severe levels of corrosion were due to the high levels of tin present in the two corroded bullets (Foard and Morris 2012, 153). However, this conclusion is based on the results of three sets of analysis and is therefore limited in scope. Sivilich has also recorded lead-tin alloy bullets from the site of Monmouth battlefield where three bullets had a content of approximately 30% tin, probably from the melting down of low-grade pewter objects (Sivilich 2016, 118). This limited previous research has suggested that increased tin content of bullets may increase their rate of deterioration.

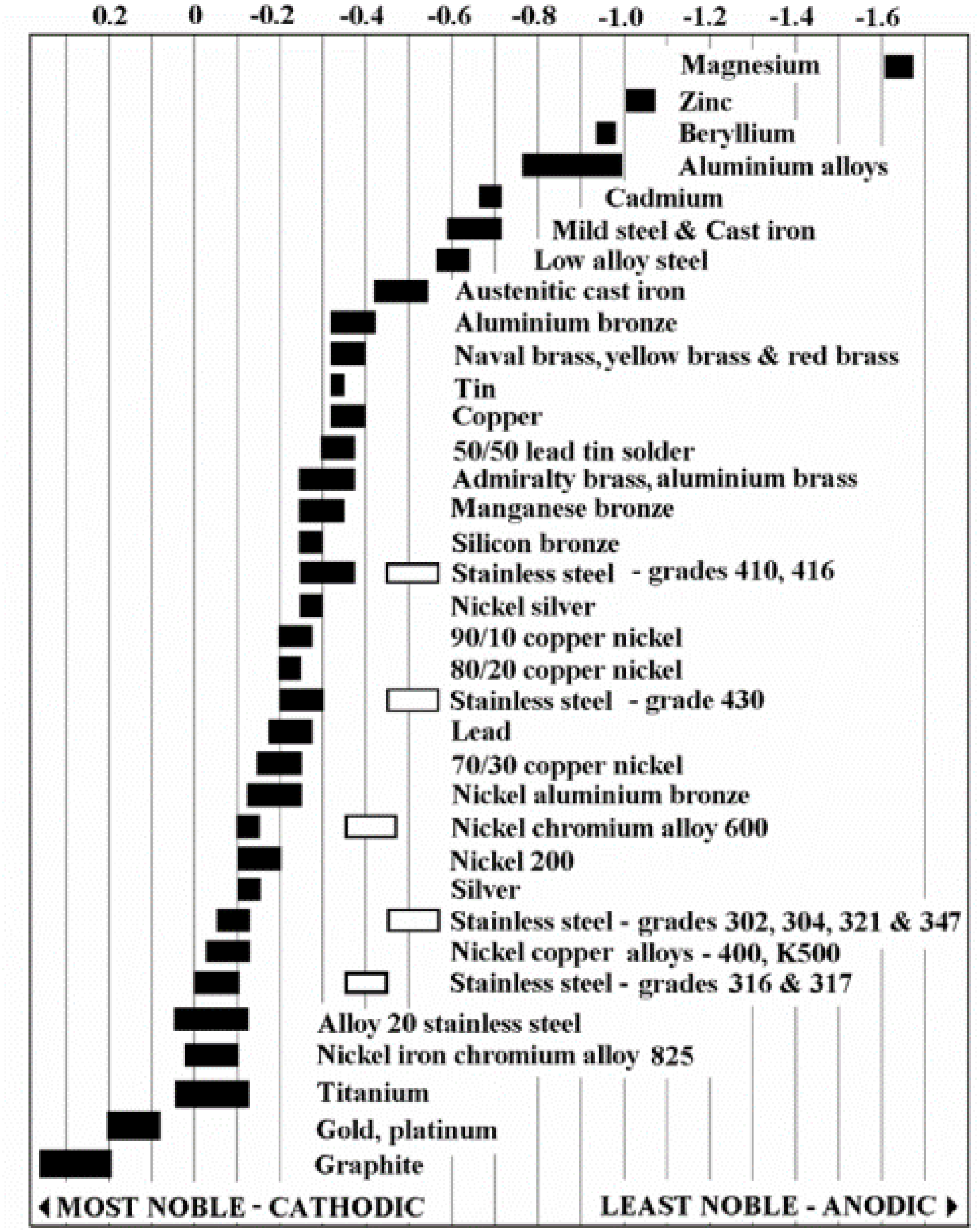
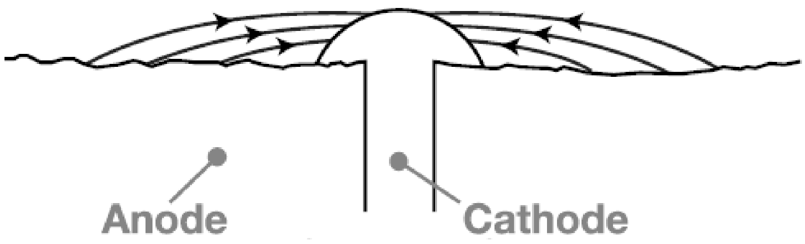
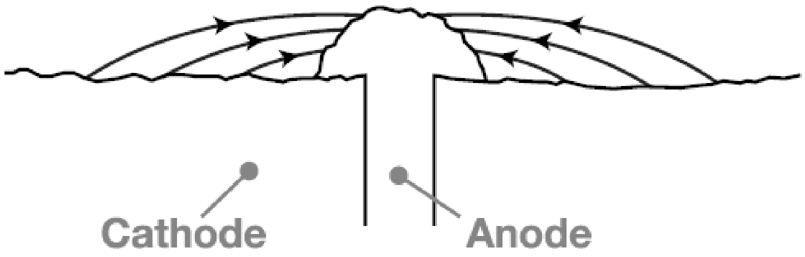


Figure 23: Galvanic series of metals in seawater (Verink Jr 2006, 99).



A) Large anode area, small cathode area showing relatively insignificant attack over a wide area of sheet.



B) Large cathode area, small anode area showing relatively pronounced attack of the rivet head.

Figure 24: Cathode to anode area ratio and its effect on corrosion rate (National Physical Laboratory 1982, 6). This shows that with a small anode area (tin) and large cathode area (lead) the rate of corrosion of the anode is increased.

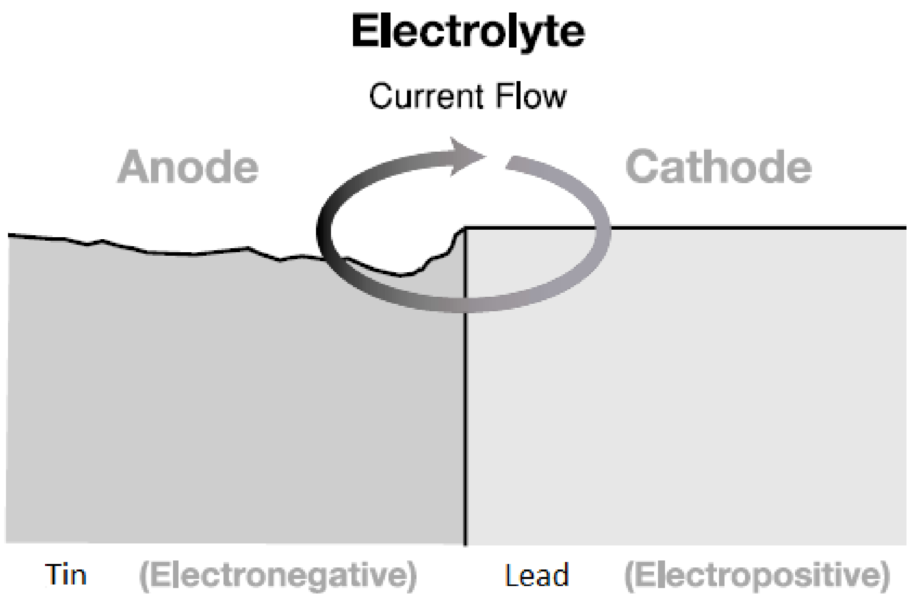


Figure 25: Bimetallic corrosion cell of lead and tin, showing the increased corrosion of anodic tin. Adapted from National Physical Laboratory (1982).

3.3.9 Overview of lead corrosion

It is clear that certain aspects of an object's environment promotes or hinders preservation. If lead is to remain stable it needs to avoid intense heat, high relative humidity (RH), low pH levels, pollutants and nitric and acetic acids (Costa and Urban 2005, 57; Cronyn 1990, 204). Changes in these parameters can trigger active corrosion (Logan 2007, 1). Lead will also become brittle over time and if under the influence of stress, from compaction and movement in the ground, lead can become fragile, crack and this can initiate further corrosion (Rimmer *et al.* 2013, 12-13).. This is a serious concern in ploughsoil contexts where objects will be constantly disturbed by the cultivation of the soil. Experiments on the corrosion of lead cells have shown that continuous wetting and drying can distort the morphology of lead patina, and the fluctuations in moisture content can cause environmental agents access to the underlying metal through intergranular corrosion (Black and Allen 1999, 157).

The best environments for the preservation of lead are dry alkaline environments with little organic content; when alkalinity increases, levels of OH^- also increases as does the amount of carbonates, promoting the formation of insoluble lead carbonates (Rowell 1994, 158). A lack of water will slow the electrochemical corrosion process and lack of organic matter will reduce threats from organic acids. The worst environments for leads are acidic soils which promote the formation of soluble corrosion products. Sites with free draining soils are likely to also encourage corrosion by erosion as the soil solution moves rapidly across the surface of lead, wearing down the patinated surface and promoting stress corrosion cracking.

3.4 Establishment of a condition assessment for lead bullets

In order to assess the preservation state of lead bullets and compare assemblages, a systematic method of condition assessment needs to be applied to collections. This requires a review of past and current condition assessments to be carried out (section 3.4.2 below). Once designed for lead bullets, the methodology can then be adapted and extended to other artefact classes and metal types in future studies.

3.4.1 Understanding the condition of artefacts

The surface of artefacts contains almost all archaeological information about an object (Caple 2006, 184). This is where evidence for manufacture, use and manipulation lie. However, it is the surface of objects that are most vulnerable to damage and decay as they are exposed to their immediate environment. Decay is caused by biological, chemical and physical processes, and it is usually a combination of these that cause all materials to decay to some degree (Caple 2000, 106; 2006, 192).

As discussed in section 2.2, ploughsoils are often overlooked as not having a significant or meaningful context as deposits within them are naturally unstratified and few have studied them as a focus of *in situ* research (Dunnell and Simek 1995). Where the condition of artefacts in topsoils has been assessed it is usually on a case by case basis on individual sites where a select number of objects have been analysed (Graham and Cox 2001; Haldenby and Richards 2010).

Until the 1990s little work on the study of corrosion had provided useful information on the condition of artefacts and the relationship between metallic composition, the burial environment of objects, and how the land had been utilised since their deposition (Adams 1994, 9). Furthermore, the study of corrosion processes and kinetics over archaeological time periods is not routine (Dillmann, Neff, and Feron 2014, 567) and so it is difficult to understand and predict the rate and nature of decay, particularly in complex environments or unstratified soils. There is a necessity to develop a model in order to rate the condition of artefacts across sites in order to predict their likely future deterioration trajectory (Foard, Janaway, and Wilson 2010, 6).

3.4.2 A review of past and current condition assessments

There is no single system for assessing the condition of archaeological objects, and their condition is often not studied in archaeological fieldwork. The majority of condition assessments are carried out by museum professionals or conservators in order to identify objects that require further treatment or stabilisation before display or permanent storage. Therefore their assessments are not necessarily examining the value of data available from objects; they mainly serve to prevent further damage. In limited cases further analysis is carried out to identify composition or corrosion products, usually by X-ray fluorescence and X-ray diffraction (English Heritage 2008). Several condition assessment tools exist which are implemented by museums such as SPECTRUM and the Condition Assessment Tool (CAT)

(Collections Trust). These act as archives and monitoring procedures rather than as a direct measurement of object conditions.

Similar to curatorial museum management procedures, English Heritage use a system to keep track of the conservation of objects under their care by noting the object's stability, level of condition and to identify what level of conservation the object may require in order to propose treatment (Graham and Middleton 2012). Keene emphasises that there are several different aspects to the 'condition' of objects and summarises how materials may be assessed in a museum collection using a flow chart (figure 26) (Keene 2002, 147).

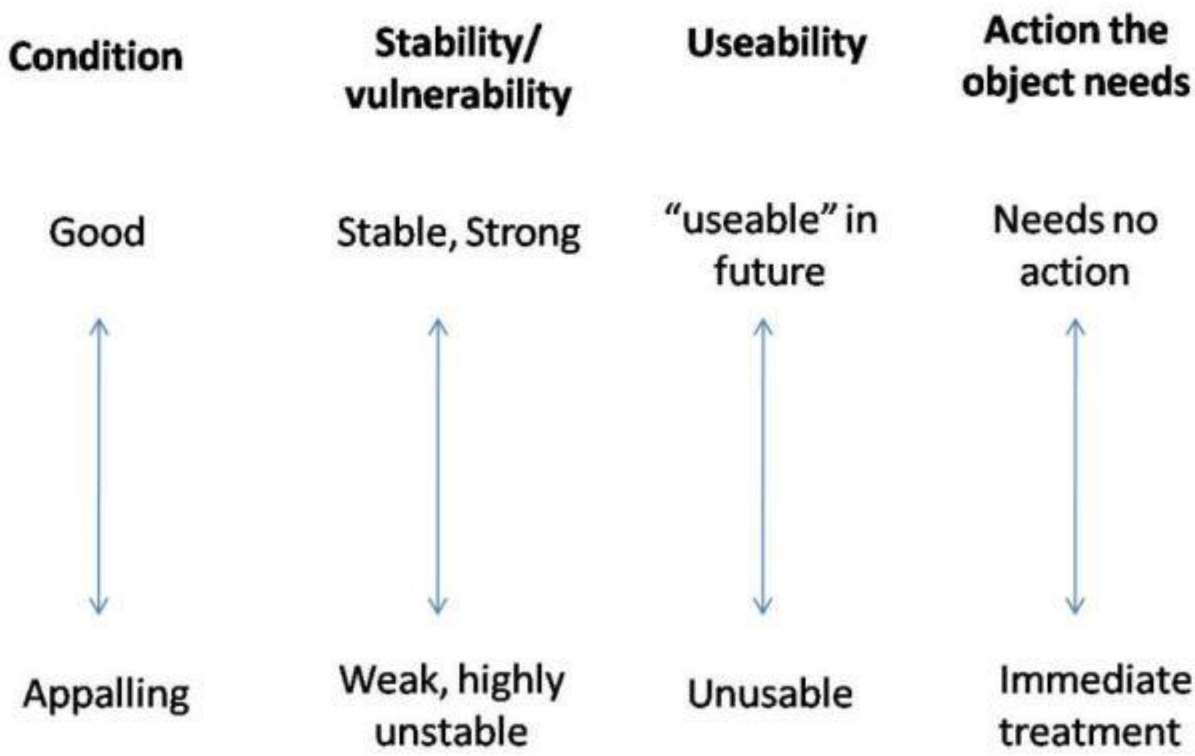


Figure 26: Flow chart for assessing the condition of museum artefacts. Adapted from Keene (2002, 147).

Sueson-Taylor and Sully (1997) report on a standard method of assessment developed for archaeological leather based on a four category visual assessment. They note that such visual assessments for archaeological materials can be subjective, but subjectivity can be limited if the condition definitions are followed closely, they are applied consistently, and a large sample is used (Sueson-Taylor and Sully 1997, 160). They conclude their method is useful for quantifying condition without the need for complex analytical assessments and is particularly useful for defining condition and allocating appropriate conservation treatment (1997, 167-168).

Neff *et al.* (2006) devised an equation to calculate corrosion rate by calculating equivalent iron thickness from corrosion product thickness. As the original dimensions of artefacts was not known, they estimated average corrosion rate based on quantifying the total amount of iron that moved out of the original metal core during the burial period (Neff *et al.* 2006, 2951).. They measured the thickness of corrosion product layers by optical microscopy and then calculated the likely iron amount that is generated by the dissolution of corrosion layers. They concluded the corrosion rate of 40 iron artefacts was under 4μm/year (2006, 2969).

In 1998 the Danish Research Council examined the *in situ* preservation of metal antiquities in soil and developed an object classification system (Madsen, Anderson, and Anderson 2004, 50). They assessed 2,225 bronze objects visually, using a grading scale to rank their condition mainly based on the colour and tarnish of corrosion products on the object's surface. This is similar to the system used by Swedish researchers studying prehistoric bronzes in the 1990s which ranks objects on a scale of 1-5 based on their surface corrosion (table 12).

Description	**Rank**
Not tarnished or little tarnished, iridescent red, brown, or black coloured	1
Green layer, thin with mother-of-pearl lustre and original surface	2
Green original surface with underlying corrosion layer	3
Thick corrosion but remaining metal in the core	4
No metal or cuprite left	5

Table 12: Condition assessment based on surface appearance of bronzes. Adapted from Madsen, Anderson and Anderson (2004, 53).

The European project No. EV5V-CT94-0516 developed a three staged ranking system to describe the condition of copper and iron artefacts across sites in the Netherlands, Greece and Great Britain (Wagner *et al.* 1998). This allowed cross comparison of assemblages of copper and iron artefacts in different countries and focused on several areas of condition; the extent of surviving metal, their stability, and visible surface detail (table 13).

Fernandes (2009) devised a scoring system for assessing the condition of copper alloy objects in soil based on several criteria (table 14). This method was further applied by Fernandes *et al.* (2013) on copper artefacts from the Roman site of Fectio in the Netherlands. They applied the classification system to 61 copper alloy objects from the site and correlated the results with data obtained from handheld XRF experiments. Their work revealed that the copper artefacts were generally in very good condition, mainly down to the formation of smooth stable patina layers due to a non-aggressive slightly alkaline clay lime-rich soil (Fernandes, Van Os, and Huisman 2013, 6). Their classification omitted the parameters 'amount of soil attached' and 'colour' from Fernandes' study (2009) as these are not direct measurements of condition.

Research was carried out on the Iron Age and Roman settlement of Owmby-by-Spital, Lincolnshire and a system was devised to assess the condition of copper and silver coins and iron nails to establish the relationship between the preservation of the objects and activity on the site (Cox and Graham 2004; Graham and Cox 2001). For coins a 1-5 scoring system was devised; coins which had detail clearly preserved in an unbroken patina scored one, whilst coins that were mineralised with a friable patina and heavily encrusted scored five (Cox and Graham 2004, 27). English Heritage have since devised a coin condition assessment criteria designed to inform identification by numismatists on the level of preservation before study (Graham Unpublished). A 10% sample of iron nails from Owmby-by-Spital was also studied (719 nails). Nails were chosen as a condition measure as they were plentiful from the site and have a distinct morphology (Graham and Cox 2001). The condition of the iron nails was measured in two stages; first by completeness and second by the degree of flaking which is a sign of active iron corrosion (table 15) (Cox and Graham 2004, 28).

Other approaches have been implemented without the use of a systematic scoring system. Gerwin and Baumhauer (2000, 68) addressed the condition of iron from sites in Germany by measuring the amount of metal core surviving through the use of X-radiographs. Dillmann *et al*. (2014, 568) measured the corrosion rate of iron by measuring corrosion layer thickness. Pollard *et al.* (2004) measured the condition of artificial coupons during experiments in Bradford purely by the percentage of surface corrosion. Haldenby and Richards (2010) measured the condition of Anglo-Saxon strap ends and pins from the ploughsoil based on the completeness of objects, focusing on the mechanical damage inflicted on objects.

Parameter	Value	Score
Rank A **Metallographical information (extent of metal core surviving)**	All metallographical information about metal core present	A4
	Metallographical information about metal core present	A3
	Metal traces that are on average smaller than the grain sizes are left	A2
	No metallographical information about metal core present	A1
Rank B **Stability of artefacts with respect to corrosion products**	One chemically and mechanically stable layer of solid corrosion products covering whole object	B4
	One chemically and mechanically stable layer of solid corrosion products covering whole surface with small failures	B3
	Patches of chemically and mechanically stable corrosion products that may form a multi-layered arrangement	B2
	No stable layer of corrosion products is detectable	B1
Rank C **Surface information of artefacts with respect to the original surface**	All surface information present, and all original surface preserved either in a metallic form or as a patina	C3
	Parts of surface information present, parts of original surface deformed	C2
	No original surface left	C1

Table 13: Three-stage ranking system for assessing condition (Wagner *et al.* 1998).

Parameter	Values	Score
Pitting	No pits	1
	Visible pitting	2
	Completely pitted	3
Preservation of surface	All details visible	1
	Details visible	2
	Surface partly degraded	3
	No original surface left	4
Preservation of shape	Object is complete	1
	Some damage is observed	2
	Object is partly deformed	3
	Object not recognisable	4
Amount of attached soil	No soil	1
	Some soil attached	2
	Half covered in soil	3
	Completely covered in soil	4
Colour	Light green	1
	Medium green	2
	Dark green	3
Corrosion scale	Not present	0
	Present	1

Table 14: Scoring system for the condition of copper alloy objects (Fernandes 2009, 57).

Attribute	Condition
Completeness	1 Complete
	2 Incomplete
Degree of flaking	A No flaking
	B Partial flaking <50% surface
	C Partial flaking >50% surface
	D Complete flaking

Table 15: Condition assessment for iron nails from Owmby-by-Spital (Cox and Graham 2004).

The condition systems mentioned above differ and have been effective in fulfilling specific needs of each study. A summary of systems and approaches can be viewed in table 16. However, some elements are too complex for non-conservation specialists who want rapid assessments of the conditions of objects without having to use X-rays or other sophisticated analytical techniques. Others are too simple, focusing purely on aspects such as colour or tarnish to rank the condition of metals. These systems have often focused on one or two metals, dismissing either lead or iron. There is justification in omitting iron from the same assessment used for other metals as iron corrodes in a very different way and is often found in very poor condition in burial contexts, in a non-identifiable form. Iron also has different decay issues; flaking of the surface and 'weeping' are issues associated with iron as opposed to other metals. When assessing the condition of metals, it is best to apply different assessment methods to each metal type as metals degrade and react in different ways.

Preservation of the surface and surface details is clearly a key aspect of an object's condition. Wagner *et al.* (1998) note that from an archaeological conservation perspective condition ranking is based on the quantity and quality of surface data present on the object (Wagner *et al.* 1998, 82). If the surface is not preserved then the artefact will be of little use for further analysis and interpretation. Other aspects of an object's condition may be more or less significant depending on the object type. Lead bullets are not likely to have suffered large post depositional breaks due to their spherical shape and stability, whereas objects with separate loose fittings such as harnesses, straps and pins to buckles are more likely to suffer breaks and loss to their percentage completeness in the ground. This also highlights the problem of identifying pre-depositional and post-depositional damage.

From the above discussions the best approach to condition assessments appears to be a multifaceted, subjective, visual approach where several aspects of the object are assessed on a ranking system. Several important aspects of condition have been highlighted as part of the above condition assessments and are laid out in table 17. Most research has utilised methods largely based on visual assessment and appear to have been effective ways of measuring condition.

Metal	Assessment	Reference
Iron	Amount of metal core surviving (X-radiography)	(Gerwin and Baumhauer 2000)
Iron	Thickness of corrosion products (modern pipes)	(Dillmann, Neff, and Feron 2014)
Iron	Completeness and degree of flaking (nails)	(Cox and Graham 2004; Graham and Cox 2001)
Iron and copper	3 ranked criteria (metal core surviving, stability, surface detail)	(Wagner *et al.* 1998)
Copper	Object completeness (mechanical damage)	(Haldenby and Richards 2010)
Copper	6 stage assessment	(Fernandes 2009)
Copper	4 level criteria (pitting, preservation of surface, preservation of shape, corrosion scale)	(Fernandes, Van Os, and Huisman 2013)
Bronze	Surface corrosion description (1-5 ranking)	(Madsen, Anderson, and Anderson 2004)

Table 16: Summary of condition assessments applied to different metals discussed in text.

Condition aspect
Stability and appearance of corrosion products
Remaining metal core surviving
Survival of original surface
Object completeness or surviving shape
Surface preservation
Degree of pitting
Thickness of corrosion product

Table 17: Aspects of artefact condition regularly assessed in ranking systems.

3.4.3 Condition assessment applied to lead bullets in this study

In order to collect more data on the condition of metal objects in topsoils a selection of lead bullet assemblages is analysed in this research, recovered through metal detecting surveys from three 17th-century Civil War sites of conflict in England. The analysis of a common artefact type from sites that have been well recorded and processed means the methods applied in this study will have wider implications and can be applied to other current and future metal assemblages.

An assessment has been derived adapted from systems discussed above, which is relatively quick to apply to large collections of artefacts with the need of little analytical equipment, in order that non-specialists and field archaeologists will be able to apply it to collections immediately after objects are retrieved and cleaned from sites. Though it will give a good overview of object condition across a site in order to identify patterns in preservation, it is not intended for the conservation of long term preservation of objects as this will always require specialised conservation work.

The condition assessment focuses on the visual assessment of the surface condition of the object rather than the underlying metal. As this research focuses on how soil conditions and land use can affect the preservation of artefacts, the method addresses post depositional condition after recovery, as opposed to pre-depositional damage or alteration. The assessment has also only been carried out where artefact types can be positively identified, similar to the case of Owmby-by-Spital nails project (Graham and Cox 2001). It does not consider artefacts which are 'unidentifiable' as it is almost impossible to score an object's condition without knowing its original shape or intended purpose.

The condition assessment consists of an overall condition score, followed by a five category assessment, supplied with descriptions and images to help the assessor analyse collections (table 18). Each category is given a score of 1-4 depending on their visual characteristics, with one being very good condition and four being poor condition. A full copy of the condition scoring sheet along with images to guide the scoring process can be viewed in appendix I.

Category	Description
Smoothness of surface (SS)	Describes how smooth in touch and appearance the surface of the object is. The smoother the surface, the less pitting has occurred and the better preserved. Bullets which have significant localised corrosion, pits or globules should be noted.
Preservation of shape (S)	Describes the surviving shape of the object in terms of completeness. If an object is complete and hasn't suffered any loss of shape from being hit or damaged in the ground it will score a 1. If it has been compacted, bent, clipped or chewed it will score higher. This does not include change in shape prior to burial (e.g. impacted bullets).
Visible surface detail (SD)	Describes the clarity of surface information and features on the object in terms of visible details (cast seams, sprues, banding etc.)
Amount of corrosion products (CP)	Gives an indication of the amount of corrosion on the surface of an object. An object with a fairly consistent single coloured surface will score low, but an object with several different corrosion products on the surface which is obscuring detail will score higher.
Stability of surface layer (ST)	Describes the stability of the surface layer as opposed to the underlying metal. Low scores are given if the surface has formed a solid patina. Higher scores will be given if the surface layer has been partially lost, the patina has faults or is flaking, powdery, or eroded (signs of active corrosion).

Table 18: Condition assessment categories utilised in present research. A complete worksheet of individual scores can be seen in appendix I.

3.4.4 Difficulties and limitations of the condition assessment

Many difficulties arise when assessing an object's condition. Its period in the ground, the method of collection and retrieval from sites, as well as the way it has been treated and stored during post excavation will all affect its condition. The benefit of lead bullets is their almost immediate usage since they are only fired once and are not usually recovered and re-used and therefore we can determine almost to the exact day when they entered the soil.

The condition of collections will also have deteriorated since recovery. It is often difficult to identify what damage or loss of data has occurred at what stage; for instance, whether a bullet has been dented during its use as it was rammed down the gun barrel, or whether it has been accidentally dropped and dented during post excavation. Sometimes this is clear; a quartered bullet was clearly pre-depositional alteration to shape and has nothing to do with ground conditions (Sivilich 2016, 74). Nonetheless there will always be an amount of interpretation and level of human error in any visual assessment method and this degree of error needs to be taken into consideration. A relatively large sample size of 569 bullets is utilised in this study to reduce subjectivity, as advised by others in previous work (Sueson-Taylor and Sully 1997).

3.4.5 Bullet condition assessment testing exercise

The condition assessment was tested by a group of nine participants; all archaeologists or historians of varying backgrounds, to see how useable the system was and how results differed between assessors. Six bullets were selected at random from available samples to create a 'test group'. Each individual was provided with a condition assessment worksheet (appendix I) and a hand lens. The author supplied a score for each bullet as a control for the assessment.

3.4.5.1 Test feedback

All participants agreed it was a coherent assessment of surface condition that would be highly applicable and useable for archaeological finds officers who need to establish the condition of objects swiftly. The Finds Liaison Officer suggested it may be slightly complex for PAS to utilise, but could be adapted into a computer based drop-down function on their online database. Overall the system would probably suit post excavation assessment of large collections going in to storage and for research purposes.

Individuals were deliberately chosen to carry out the exercise that had diverse archaeology backgrounds in order to establish how much knowledge and expertise is required in order to assess the objects. It became apparent that a certain amount of knowledge about lead and projectiles was needed in order to understand the quality of surviving detail. Images were provided with the worksheet, but more detailed aspects, such as quartered bullets being deliberately cut rather than being affected by their burial environment were not explained in the document. Some scored the condition based on the patina colour, which is not an accurate method and struggled with their lack of corrosion knowledge. Further basic training on this could be provided if the assessment was carried out on a larger scale, both in identifying bullet surface details and in general corrosion knowledge. Participants are numbered by their profession, as laid out in table 19.

Number of participant	Occupation
1	Finds illustrator
2	Field archaeologist
3	Finds Liaison Officer
4	Curator 1
5	Curator 2
6	Independent researcher 1
7	Independent researcher 2
8	Battlefield archaeologist 1
9	Battlefield archaeologist 2

Table 19: Numbers used to refer to participants and their occupations.

3.4.5.2 Test results

All participants completed the assessment of six bullets within 30 minutes. Most used the supplied x10 magnification hand lens as some details are not evident to the naked eye.

Abbreviations used in assessment:
SS- Smoothness of surface
S- Preservation of shape
SD- surface detail
CP- corrosion products
ST- Stability of surface

Bullet 1: MOR 0122 (figure 27)

Control score	SS	S	SD	CP	ST	Overall
	3	1	3	3	3	3

Table 20: Control score supplied by author for bullet 1 (MOR 0122).

Figure 27: Test bullet 1 (MOR 0122).

There was some variation in scores for bullet 1. The majority of scores did not stray more than one point above or below the control score given by the author (table 20). The total score of the five condition categories added up to between 9 and 15, with 13 as the total control score (figure 28).

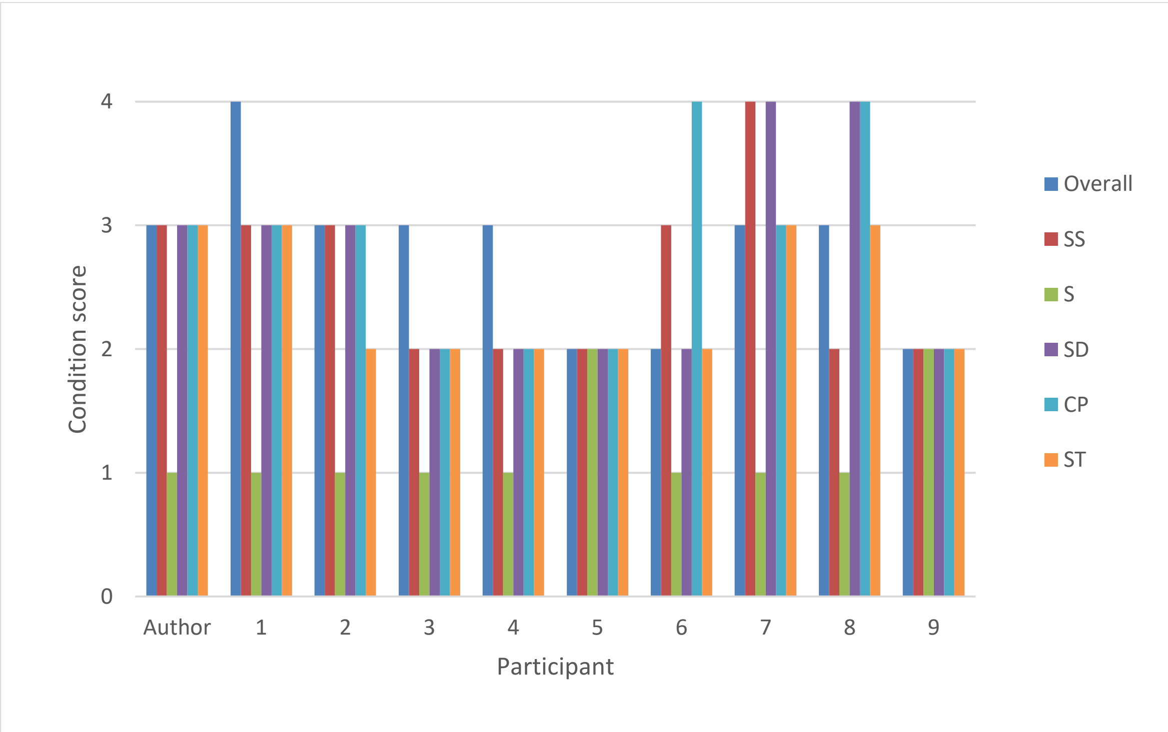


Figure 28: Results of assessment for bullet 1 (MOR 0122).

Bullet 2: MOR 0133 (figure 29)

Control score	SS	S	SD	CP	ST	Overall
	2	1	2	1	2	2

Table 21: Control score supplied by author for bullet 2 (MOR 0133).

Figure 29: Test bullet 2 (MOR 0133).

The results for bullet 2 were fairly consistent, apart from preservation of shape. The bullet is quartered, cut prior to use as buck shot. However, three participants (1, 3, and 4) have interpreted this as damage to the shape (figure 30). It must be made explicit that the condition assessment is intended to analyse post depositional damage and alteration, though lack of knowledge of the artefact type may have hindered this process.

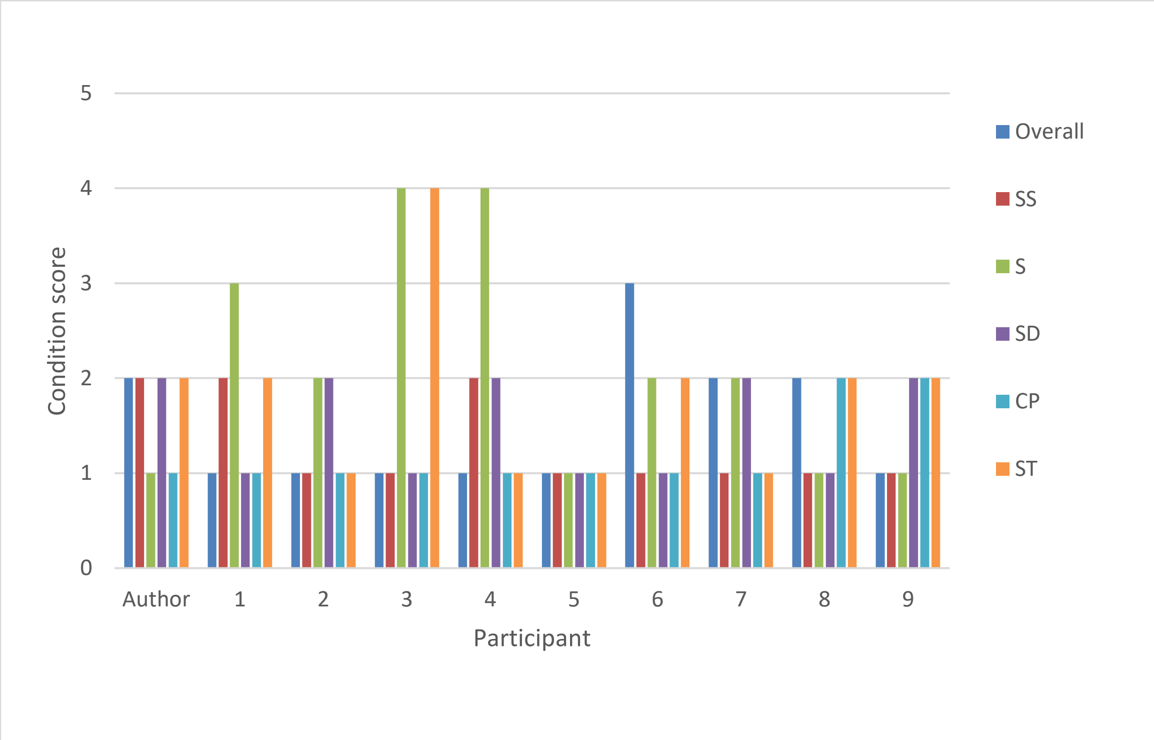


Figure 30: Results of assessment for bullet 2 showing fairly consistent results (MOR 0133).

Bullet 3: MOR 0136 (figure 31)

Control score	**SS**	**S**	**SD**	**CP**	**ST**	**Overall**
	1	1	2	1	1	1

Table 22: Control score supplied by author for bullet 3 (MOR 0136).

Figure 31: Test bullet 3 (MOR 0136).

The scores produced for bullet 3 were consistent with the control score. However, one score stands out; participant 3's score of 4 for stability of surface (figure 32). On questioning the participant they had assumed the whitish patina on the bullet meant that it was actively corroding. However, this would need to be powdery, flaking or degrading to be of poor stability. This reiterates the need for some prior knowledge on metal artefacts and an understanding of metal degradation.

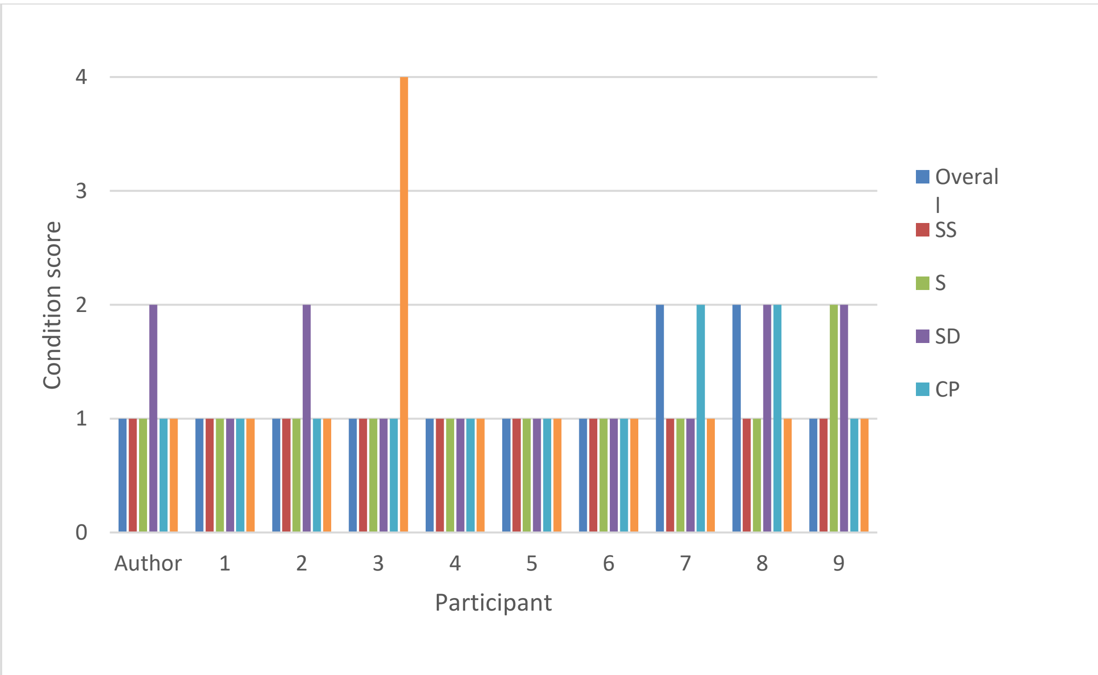


Figure 32: Results of assessment for bullet 3 showing fairly consistent results (MOR 0136).

Bullet 4: EDG 2172 (figure 33)

Control score	SS	S	SD	CP	ST	Overall
	2	2	2	3	2	3

Table 23: Control score supplied by author for bullet 4 (EDG 2172).

Figure 33: Test bullet 4 (EDG 2172).

Bullet 4 scored quite variably. Some participants have given scores similar to the control, whilst others have given scores considerably higher or lower. Both battlefield archaeologists (8 and 9) who are bullet specialists scored the bullet lower than the control, though their focus was on visible surface detail rather than corrosion which they admit they overlooked in their assessment (figure 34).

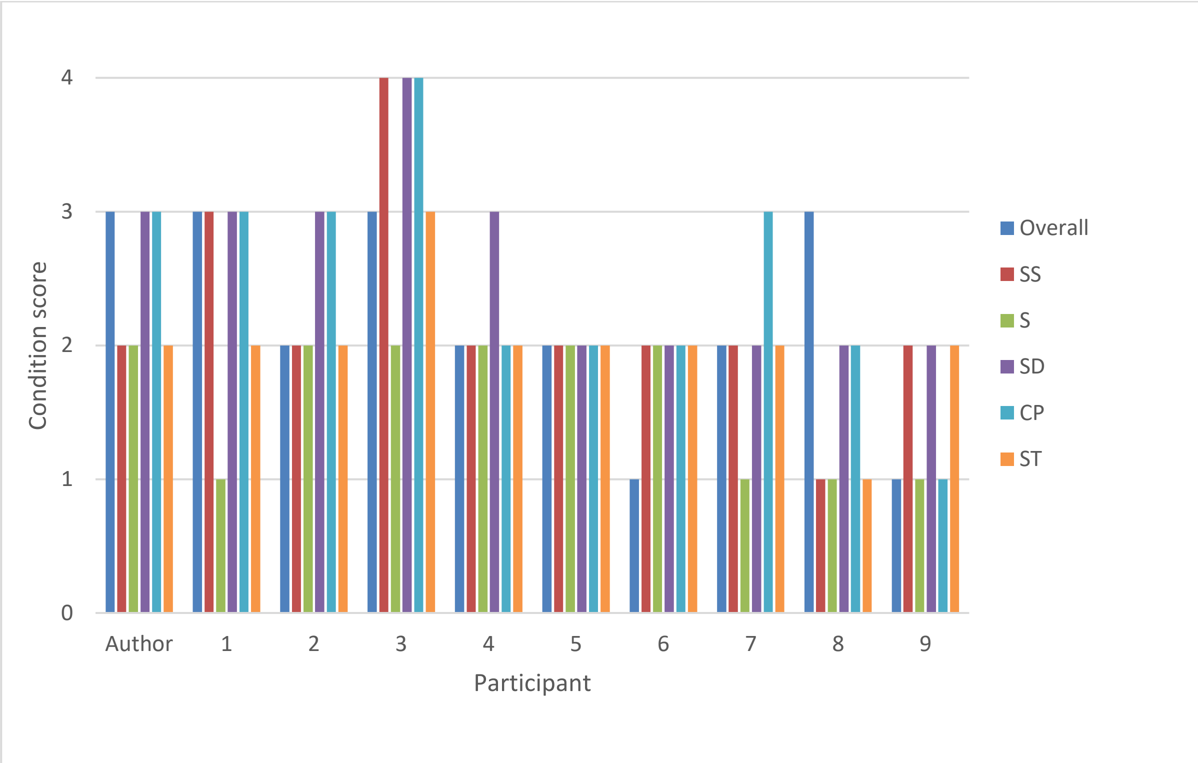


Figure 34: Results of assessment for bullet 4 (EDG 2172).

Bullet 5: EDG 382 (figure 35)

Control score	SS	S	SD	CP	ST	Overall
	1	2	1	1	2	1

Table 24: Control score supplied by the author for bullet 5 (EDG 382).

Figure 35: Test bullet 5 (EDG 382).

The majority of scores for bullet 5 are very similar to the control with all scores of one or two without counting the single score of four applied by participant 3 which is down to lack of understanding of metal patination (figure 36). The total score of the five categories ranges from 6-8, with 7 being the control. Five assessors noticed the bullet had been impacted post-depositional due to the change in patination.

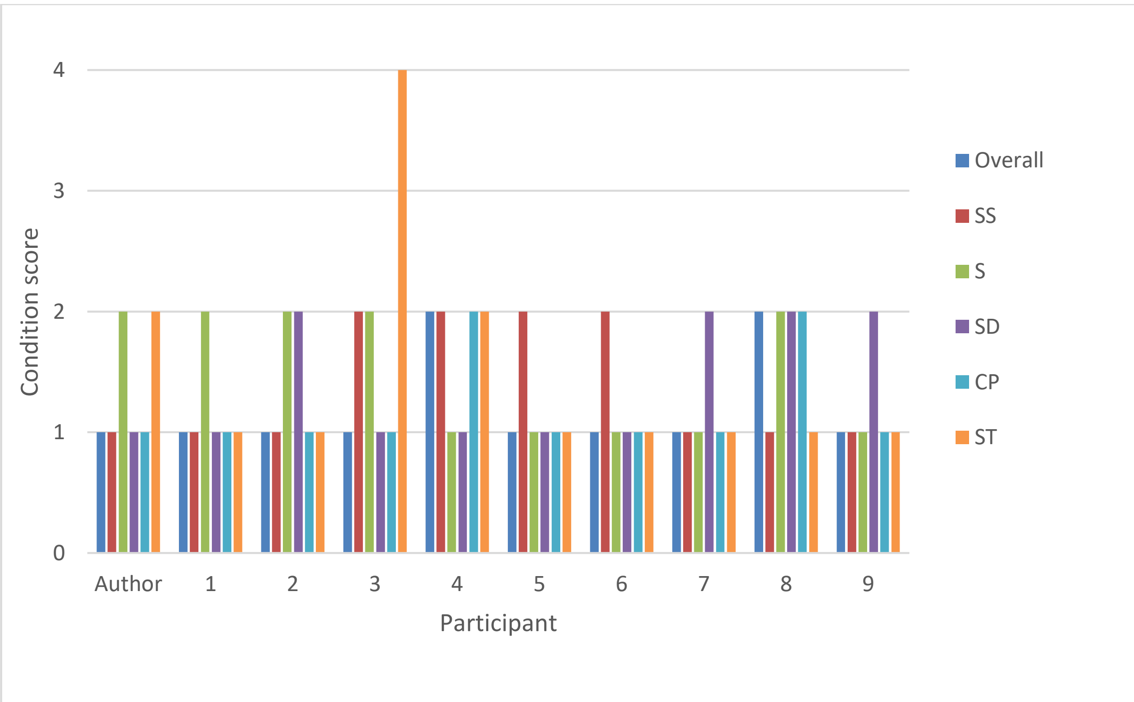


Figure 36: Results of assessment for bullet 5 showing fairly consistent results (EDG 382).

Bullet 6: EDG 2141 (figure 37)

Control score	SS	S	SD	CP	ST	Overall
	2	1	1	2	2	2

Table 25: Control score supplied by the author for bullet 6 (EDG 2141).

Figure 37: Test bullet 6 (EDG 2141).

Bullet 6 also caused some scoring issues. The control scores it in good condition, but the total scores added up from the assessors ranged from 5-14 (figure 38). Participant 8 gave the bullet a perfect score of five with a score of one in each category, though others have identified it to be in poorer condition. When questioned participant 8 focused on the quality of preserved surface detail as opposed to overall condition, whereas others viewed the varied patination as a sign of deterioration.

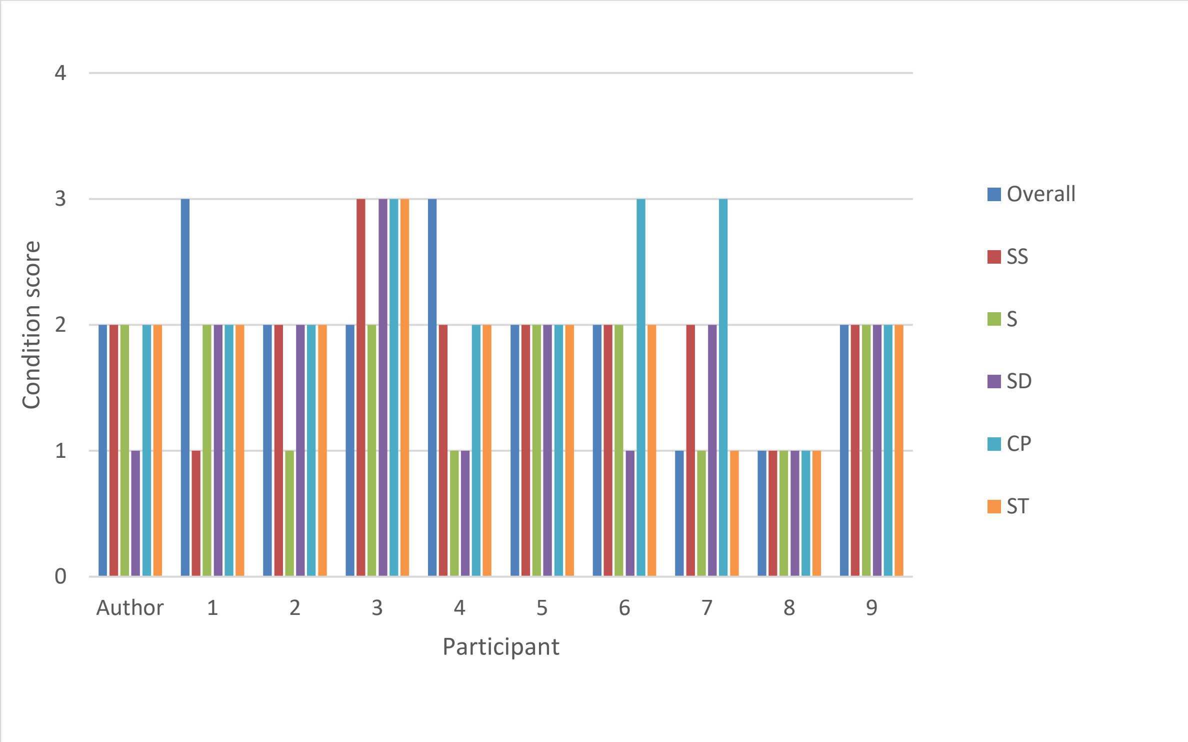


Figure 38: Results of assessment for bullet 6 (EDG 2141).

3.4.6 Overview of assessment

It is clear that there are some issues in regards to people's knowledge when attempting to rank objects on their condition. Some general knowledge of the object type and its attributes is essential, as well as some basic knowledge of lead corrosion and patination. Nonetheless, in the majority of cases, scoring did not stray far from the control score. There will always be an amount of human error and personal opinion in a visual assessment. It is important when analysing a collection that the same person or people apply a consistent method in a systematic way to avoid as much error as possible. The current study examines 569 bullets from three sites, and by using a large dataset and following the condition definitions closely and consistently, subjectivity and can be limited.

4 Methodologies: desk-based, field and laboratory techniques

4.1 Synopsis of case studies

Three sites of conflict provide the case studies for this research. The location of each site is shown on the map (figure 39). An overview of the sites, their approximate coverage and size of assemblage is given in table 26. The three sites vary in terms of overall artefact condition and provide variations in land use, superficial geology and soil environments for comparison. Edgehill provides a rare opportunity to assess areas of preserved distinct ridge and furrow on permanent pasture which can be compared to the condition of artefacts under arable cultivation. Moreton Corbet has a varied land use history, from being used as part of formal gardens of the 16th-century estate to recent arable cultivation. Wareham is now a quarry, but was in almost constant arable cultivation since at least the mid 19th century. Comparison between the case studies may reveal insights into the impact of historic land use on the preservation of buried assemblages.

Figure 39: location of the three sites studied in this research.

Site	**Site type**	**Size of site encompassing buried assemblage (approx.)**	**Size of area investigated in this study (approx.)**	**Assemblage analysed**
Moreton Corbet	17th-century siege site	$0.64km^2$	$0.5km^2$	177 bullets (89% of collection)
Edgehill	17th-century battlefield	$12km^2$	$2.5km^2$	112 bullets (10% of collection)
Wareham	17th-century siege site	$0.8km^2$	$0.8km^2$	280 bullets (50% of collection)

Table 26: Synopsis of selected case studies for investigation.

Several stages of analysis were carried out for each case study in order to evaluate the collections and the sites. In each site's case:

-The condition assessment was applied to a sample of the lead bullet collection

-Desk and field-based land use assessment was carried out to evaluate historic and current land use

-Desk-based research on superficial geology of sites was carried out

-Soil samples were taken across the site in order to evaluate and measure physical and chemical characteristics of the soil

-Selection of bullets were analysed for their composition and corrosion products formed to ascertain whether composition has affected preservation

4.2 Historic landscape assessment

A desk-based assessment was carried out for each site to address the land use history, soils and superficial geology of the landscape. Historic land use assessment focused on the period from the 1930s until the present day to encompass the period of modern agriculture and more reliable land use sources. Older sources are referred to where applicable. The earliest detailed assessment of land use patterns in Britain is Dudley Stamp’s Land Utilisation Survey carried out in the early 1930s (Darvill and Fulton 1998, 148). Other key sources referred to include RAF aerial photographs taken during and just after World War Two. The following sources and archives were assessed during this study:

-Historic England Archive, Swindon National Office (aerial photographs)

-County Council archives and local HERs

-Ordnance Survey maps of England and Wales 1842-1952

-LIDAR (Environment Agency 2017)

-Dudley Stamp Utilisation Survey (Ordnance Survey of England and Wales 1938)

-Tithe and estate maps (where available)

-Field observations

-Questions posed to farmers/landowners

4.3 Field methodology

Methodology in the field varied slightly due to the nature of each site. The Wareham assemblage was recovered prior to the construction of a gravel quarry and artefacts had been collected without the recording of accurate spatial data for each object. This also restricted the collection of soil samples which had to be retrieved from just outside the quarry area to avoid contamination.

The Edgehill battlefield is substantial, covering approximately 12km² with over 3,000 artefacts recovered from the systematic 2004-7 surveys (Foard 2012, 154). It was decided to sample this site based on land use type and a number of fields in the centre of the battlefield were investigated rather than the entire site which was too vast for the current study.

Moreton Corbet was a manageable site in terms of size and accessibility. The majority of artefactual evidence recorded to date lies in three fields lying to the north, east and south of the 13th century castle and surveys are still being carried out at the site, with approximately 200 lead bullets recovered to date (Leese, pers. Comm.. 06.05.2017). Initial soil sampling was conducted at this site and was developed into a systematic soil sampling strategy in order to assess the character of the entire site. Different levels of sampling were undertaken in order to ascertain how much sampling is required for an effective assessment of burial environments across a landscape.

4.4 Soil sampling

Rowell and Hodgson suggest digging and excavating a soil pit up to 1x1.5m in extent to expose the soil profile if samples are required from several horizons (Hodgson 1976, 13-14; Rowell 1994, 7). This procedure was carried out initially at Edgehill, but was too time consuming and became impractical on a large scale. A quicker and more efficient sampling strategy was therefore adopted in order to cover more ground and to provide more systematic sampling coverage at each site.

Soil samples were taken from each site close to the proximity of retrieved artefacts in order to compare the soil chemistry to the preservation of nearby objects. For each test pit a 0.30mx0.30m clod of turf/crop was removed by spade (figure 40) and then a gouge auger was used to extract a sample of the soil profile (figure 41). Depth of sampling varied depending on the soil profile depth and the ease to which the auger entered the ground.

At Moreton Corbet a Dutch auger was initially used for sampling, but a gouge auger was preferred in future surveys as it extracts a soil column sample much neater without causing mixing of soil layers (figure 42). It also comes installed with a hammerhead which makes driving it into the ground much easier, and a handle for extraction. As Edgehill comprises very compact clay, a Dutch auger continued to be used as a gouge auger could not penetrate the dense clay.

An attempt was made at extracting bullets surrounded by their soil matrix in a block. However, this approach was impractical for this project as it required the detection and retrieval of bullets at the same time as the soil matrix which proved unfruitful. At the time of this study a full scale survey was not in progress and recovery of artefacts was slow. However, there is potential in future to combine the collection of soil samples during metal detecting surveys so that bullets could be extracted with their surrounding soil matrix.

Matthiesen (2004) suggests taking measurements such as pH *in situ* with an electrode probe is the ideal strategy as this reduces possibilities of soil oxidation. However, Rowell states that using a probe can disturb the soil and measurements can be taken much more systematically in the laboratory (Matthiesen 2004, 1374; Rowell 1994, 7). For this study, soil samples were collected in polythene airtight grip seal bags with approximately 500g collected from each soil horizon. These bags were then transported to the University of Huddersfield and kept at room temperature away from light sources to restrict any bacterial growth. All samples were retrieved and tested in the laboratory as probes were not available for onsite measurements. All laboratory tests were conducted within one month of sampling to allow consistent and repeatable results to be produced.

Figure 40: Example of an excavated test pit, Moreton Corbet.

Figure 41: Gouge auger in two sections with handle and hammerhead pieces showing extracted soil column.

Figure 42: Descriptions of a gouge auger and a Dutch auger used in this study.

4.5 Laboratory methods

4.5.1 Soil analysis

Soil characteristics chosen for analysis in this research are based on soil corrosivity attributes discussed in section 2.1 and summarised in section 2.3.4. Table 27 presents a summary of selected soil tests carried out in this research. Three readings were taken for each soil sample and an average produced.

Soil test	Method	Reference
Colour	Munsell chart	(Munsell Color 2000)
Texture	Field classification tables and selective particle size analysis using Malvern Mastersizer 2000	(British Standard 2007a, 2009; Gee and Or 2002; Malvern Instruments Ltd 2007; Museum of London 1994)
pH	pH probe	(British Standard 2005; Head 1980; McGrath and Loveland 1992; University of Huddersfield 2013)
Water content	Oven dried	(Avery and Bascomb 1974, 14; British Standard 2007b; Rowell 1994)
Organic content	Loss on ignition	(Avery and Bascomb 1974; Bascomb 1982; British Standard 2007b; Rowell 1994)
Conductivity	Conductivity probe	(British Standard 1995)
Chloride content	Potentiometric titration using Cl^- selective electrode	(NICO 2000 2016a; Rowell 1994, 150; Watson and Isaac 1990)
Nitrate content	Potentiometric titration using NO_3 selective electrode	(NICO 2000 2016b)

Table 27: Full list of soil characteristics analysed during this study.

4.5.1.1 Colour measurement

All soil colours were recorded using a Munsell Soil Colour Chart (Munsell Color 2000). Colour was recorded for wet, dry and ashed samples as the shade will vary depending on the water content (Gerrard 2000, 39; Hodgson 1976, 15). Munsell describes colours by their *hue, value* and *chroma*. Hue indicates a soil's relation to red, yellow, blue and purple. Value refers to a soil's lightness, and chroma indicates the colour strength intensity. Soil colour will vary depending on the organic matter content, water content, and the presence of iron and manganese oxides (Brady and Weil 2002, 122).

4.5.1.2 Texture measurement

There are numerous ways to measure soil texture (Loveland and Whalley 2001; Ryzak, Bieganowski, and Walczak 2007). The most common assessment in the field is to take a small amount of moist soil between the fingers and to assess how smooth or gritty it feels, how easy it stains the hands, and how easily it rolls into a ball (Museum of London 1994; Rowell 1994, 10).

For a more accurate measurement of particle ratios, soils can be analysed by sieving and sedimentation. A set of sieves separates fine from coarse particles. For particles <0.06mm sedimentation must then be applied, by using either a hydrometer or pipette method (Sugita and Marumo 2001). Sedimentation separates silts and clays based on the Stokes' Law principle that particles settle in a liquid over time depending on the size of the particle, its density and the properties of the liquid. Fine particles will take longer to settle than coarse particles (Hassan 1978, 205). Sedimentation is a long and arduous process with clays taking days, even weeks to settle and it is now more common to use laser diffractometry equipment.

For this research texture assessments were made in the field using a flow diagram (figure 43) (Museum of London 1994). Selected samples were further analysed using a Malvern Mastersizer 2000 to analyse particle sizes. The percentage of given particle sizes were then checked against the UK texture triangle (figure 44). Though much research utilises the USDA textural class system, the UK system was used here; they are essentially very similar although the British system utilises 60µm as a limit between fine sand and silt whereas the US system utilises 50µm (Rowell 1994, 19).

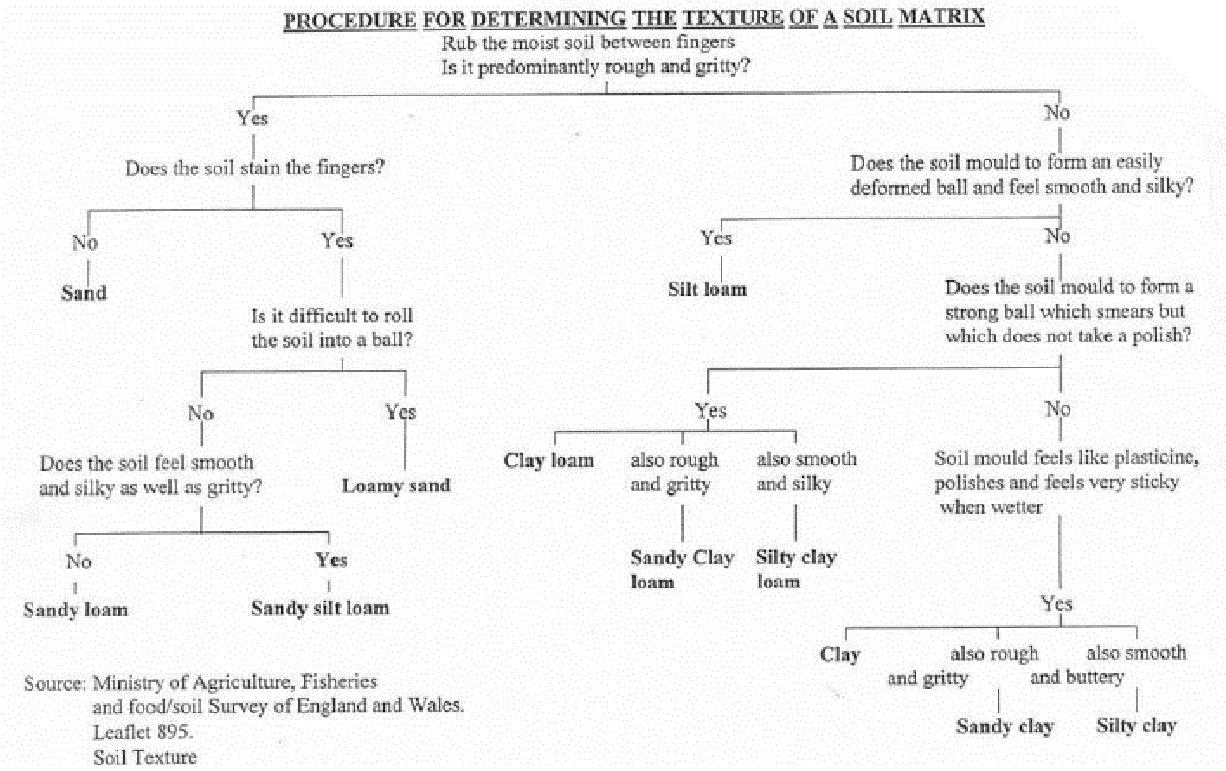


Figure 43: Texture classification chart used in this research for field assessments (Museum of London 1994).

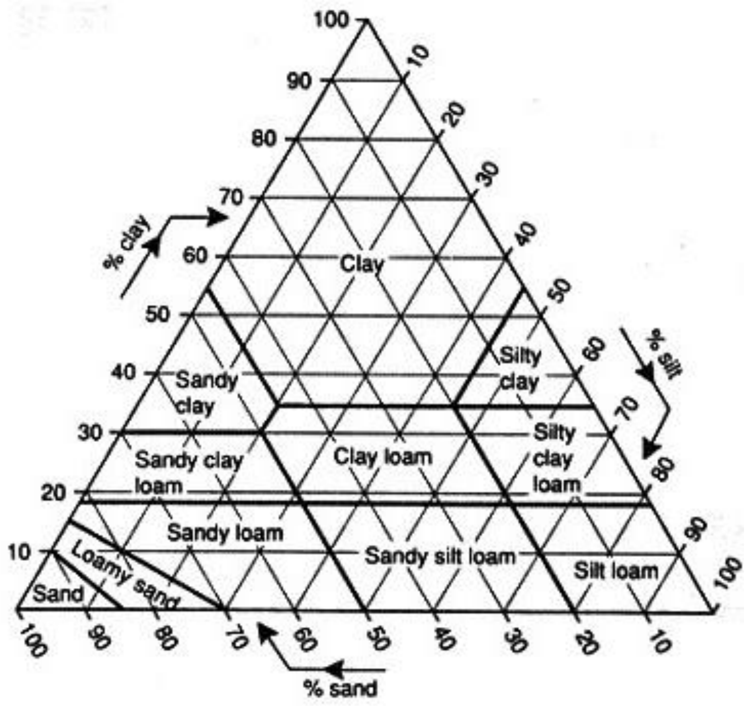


Figure 44: European/UK texture triangle for clay, sand and silt ratios, used in this research (Cranfield University 2017; Rowell 1994, 28).

4.5.1.2.1 Laser diffractometry

For this research laser diffractometry was used to test soil texture in the laboratory. A Malvern Mastersizer 2000 with a hydro 2000MU pump was used. Background to this machine and optimal settings for its use is provided in appendix II. Most importantly, research has indicated that laser diffractometry can record any particle under 8μm as a clay, as opposed to the standard cut-off of 2μm and so for this study clays are recorded as smaller than 8μm (Konert and Vandenberghe 1997, 533).

The refractive index was set at 1.63, with absorption of 0.01. Samples were initially ashed at 500±10°C to remove all moisture and organic content. It is important that organic matter is removed so that the instrument only measures soil particles. An attempt was made to separate particles using a pestle and mortar and then using a ball mill at 400rpm for five minutes. This made a significant difference to the particle size results, though on further discussion and research it was agreed that ashing samples may have altered the structure of the clay particles through the process of vitrification (Canti Pers. Comm.. 01.06.2017). It was also concluded that milling soils may affect the natural structure of the particle sizes in the soil, particularly as prolonged milling can cause structural changes to clay particles (Maleki and Karimi-Jashni 2017; Valaskova *et al.* 2011; Vdoric *et al.* 2010). The ashing and milling preparation approach was therefore abandoned. Details of how optimal methods were achieved for this project through a process of trial and error can be seen in appendix II.

Further soil samples were oven dried at 110±10°C for approximately six hours and then sieved using a 2mm sieve to remove any gravel. 10g of soil was then immersed in 20ml of hydrogen peroxide (H_2O_2) (200ml of 100 volume) to chemically eradicate the organic matter, and left to stand with occasional stirring until frothing ceased. A further 40-80ml of H_2O_2 was added depending on the quantity of organic matter in the sample and then heated. 1ml of triton X-100 was added to reduce frothing. Once frothing ceased samples were boiled to complete the destruction of organic matter to form a paste (Rowell 1994, 29). Approximately 2-3g of the soil paste was then dispersed in 30ml of sodium hexametaphosphate (1% solution) for up to 24 hours (Dias 2014; Sperazza, Moore, and Hendrix 2004). A beaker containing 800ml of deionised water was placed under the pump and set at 2000rpm. The soil dispersion was then added until obscuration reached 10-20% which is the optimal range. Ultrasonication was applied for 60 seconds to agitate particles and avoid flocculation of clays. Five readings were taken for each soil sample and then an average result was produced. The pump was washed thoroughly at least three times between each sample to create optimum background levels. The set-up is summarised in table 28.

Parameter	Setting
Soil preparation	Oven dried at 110±10°C, sieved Organic matter killed using hydrogen peroxide Dispersed in 1% sodium hexametaphosphate for up to 24 hours
Obscuration	10-20%
Pump speed	2000 rpm
Refractive index	1.63
Absorption	0.1
Ultrasonication	60 seconds

Table 28: Parameters utilised for this research for laser diffractometry.

4.5.1.3 pH measurement

pH can be measured using indicator strips, though this method is not very accurate and can only result in a 0.5 accuracy (Head 1980, 225). A more accurate measurement uses a combined pH and reference electrode under laboratory conditions using a 1:2.5 or 1:5 soil to water ratio (Head 1980, 237; McGrath and Loveland 1992, 4; Rowell 1994, 160; British Standard 2005).

The standard laboratory method involves mixing the soil sample in deionised water and measuring the solution with a pH probe, which measures the *active* acidity in the soil solution. Calcium Chloride ($CaCl_2$) can then be added causing cation exchange between the soil particles and soil solution which releases H^+ into solution. This is known as the *reserve* acidity as it measures H^+ ions released from the soil particles themselves and is deemed a more accurate method of measuring acidity as it is less affected by soil electrolyte concentration (Rowell 1994, 161; Minansy *et al.* 2011). For soils with a negative charge this addition of $CaCl_2$ causes cation exchange with H^+ being displaced into solution making pH readings about 0.5 units lower than water readings (figure 45). For soils with a net positive charge H^+ is adsorbed onto reactive sites and the pH increases (Rowell 1994, 161).

Even though pH using $CaCl_2$ is a much more accurate measurement of soil pH, much research still quotes H_2O pH. This is usually so results can be compared to historical recordings from others sites, or through a sheer lack of knowledge of the $CaCl_2$ procedure (Minansy *et al.* 2011; Schofield and Wormald Taylor 1955; Townsend 1973; White 1969). The UK Soil Observatory utilises $CaCl_2$ pH in their data due to its accuracy and reproducibility (Emmett *et al.* 2010). In this research both water and $CaCl_2$ pH will be measured, though $CaCl_2$ will be the main measurement discussed, with the H_2O pH in brackets where necessary e.g. pH 7.44 (8.05).

pH was measured in the lab in the following way:

-Calibration of Jenway 3510 pH meter using buffer solutions pH 4 and 7
-Fill a test tube with 5g of crushed air dried soil
-Add 10ml of deionised water and shake for 10-15 minutes
-Measure the pH, then add 10ml of $CaCl_2$ (0.04M concentration) and shake for 10-15 minutes
-Wait for the soil to settle and measure the pH by suspending the probe without disturbing the sediment to measure *reserve* acidity

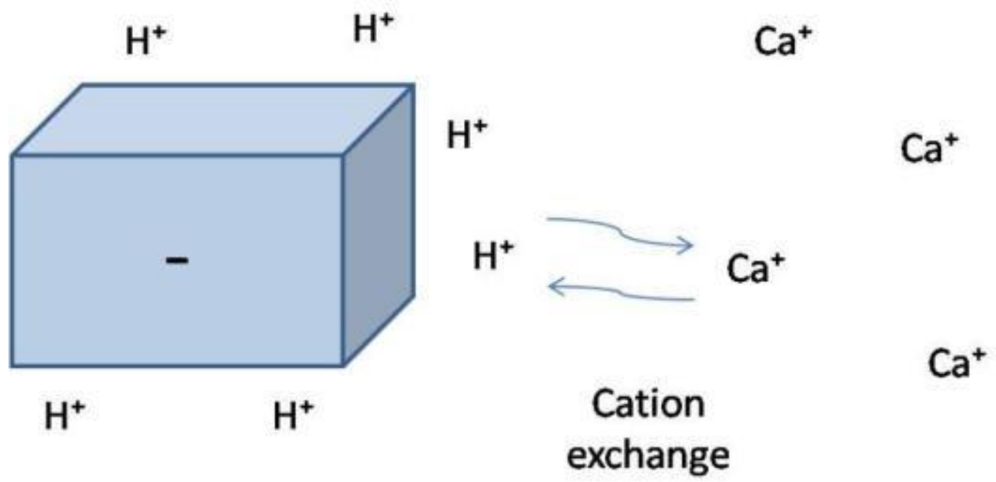


Figure 45: Cation exchange between Ca^+ and H^+ when $CaCl_2$ is added to solution, releasing H^+ into the soil solution.

4.5.1.4 Water content measurement

Soil moisture content is measured through heating to 105°C to evaporate the moisture (British Standard 2007b; Rowell 1994, 48).

-c. 5g of un-dried soil sample is lightly ground and weighted
-Place in an oven at 105±5°C until a constant rate is reached within 0.1g accuracy. This takes between 4 and 24 hours
-Moisture content as a percentage by mass is calculated:

$$\mathrm{Wm} = \frac{(\mathrm{mW} - \mathrm{mD})}{(\mathrm{mW} - \mathrm{mT})} \mathrm{X}\,100$$

Wm= moisture content
mW= mass in grams of wet sample plus tray
mD= mass in grams of dried samples plus tray
mT= mass in grams of empty tray

4.5.1.5 Organic matter content measurement

Organic matter content is measured through loss on ignition as organic matter will decompose at temperatures over 500°C (Bascomb 1982; British Standard 2007b; Rowell 1994, 48).

-Carry out water content method (see above)
-Place oven dried sample in furnace at 500±10°C for at least 2 hours to burn off organic matter
-Weight loss is calculated as a percentage of organic matter (OM)

$$\frac{(\text{mass of oven dry soil} - \text{mass of ignited soil})}{(\text{mass of oven dry soil} - \text{tray})} \text{ x } 100$$

4.5.1.6 Conductivity measurement

The most accurate method to measure conductivity is in the laboratory by mixing soil in a water solution to dissolve the electrolytes with a 1:5 soil to water ratio. In this study it was measured systematically under laboratory conditions using a conductivity meter calibrated using a potassium chloride solution, following the guidelines in the British Standard method (British Standard 1995).

-Fill a test tube of 5g of crushed air dried soil
-Add 25ml of de-ionised water
-Shake the test tube for 30 minutes on a mechanical shaker
-Lower the conductivity probe into solution and record reading

4.5.1.7 Anion content

Many anions are present in soil solutions and ideally individual anion content of soils would be tested to assess each element in turn. For this study, conductivity has been tested to measure overall salt content as well as chloride and nitrate content as they are two elements noted as being particularly dangerous to metal preservation and are present in most fertilisers applied to arable crops (see section 2.3.3.9).

4.5.1.7.1 Chloride content measurement

Chloride levels in soils can be measured with test strips (e.g. Quantab) which are submerged in solution. This method is quick, but not very accurate. The method used for this research is potentiometric titration using ion-selective electrodes measured in mg/kg (Rowell 1994, 149-151; Watson and Isaac 1990; NICO 2000 2015).

-Ion selective electrode for chloride ion (ELIT 8261) is calibrated using a series of – known standard solutions (KCl)
-Prepare four standard solutions of KCl (1ppm, 10ppm, 100ppm, 1000ppm)
-For initial calibration submerge the probe in 1000ppm overnight
-Add 2mls of buffer (5M $NaNO_3$) to each standard solution, attach reference electrode (double junction lithium acetate ELIT 003), measure solutions and plot calibration curve (figure 46)
-Weigh 4g of air dried soil, add 50ml of deionised water and mix on a mechanical

shaker for an hour

-Filter off the residue and dilute solution to 100ml. Add 2ml of buffer, stir well and take measurement

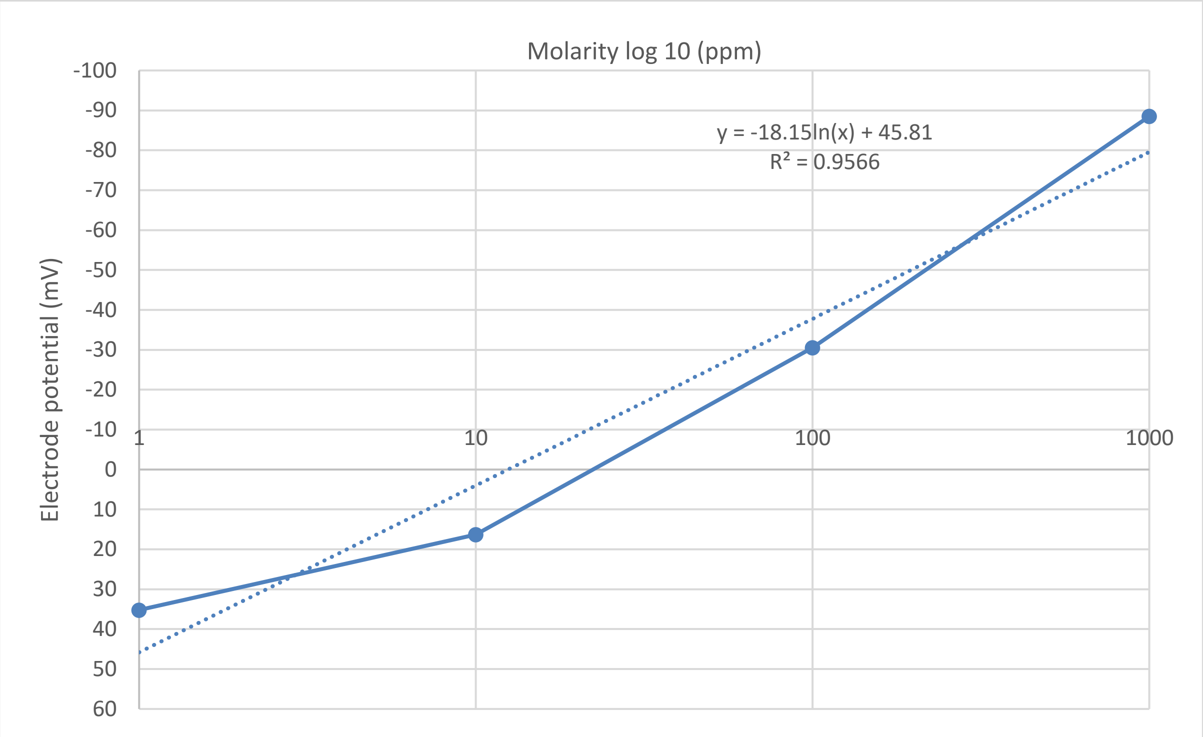


Figure 46: Calibration curve for chloride probe.

The ppm standards were graphed logarithmically to create a straight line. The following equation applied to the calibration graph:

$$y = m(\ln)x + c$$

y= mV reading

m= gradient of curve

c= y intercept

x= ppm (parts per million)

To convert the mV readings for each sample to ppm the following calculation was carried out:

$$(\ln)x = \frac{y - c}{m}$$

As a log was applied, the exponential must be taken:

$$e^{\ln(x)} = x$$

Once samples have been converted from mV to ppm, they must be multiplied by 100 and divided by the sample weight to give a concentration in mg/kg in the soil sample:

$$\mathrm{mg/kg} = \frac{\mathrm{x} \times 100}{\text{sample weight}}$$

The chloride probe is only sensitive to measurements >1ppm and therefore the accuracy of measurements between 1ppm and 10ppm is limited. Unfortunately, all measurements taken in this study were between 1ppm and 10ppm so a calibration curve using these two standards was applied to the results (figure 47).

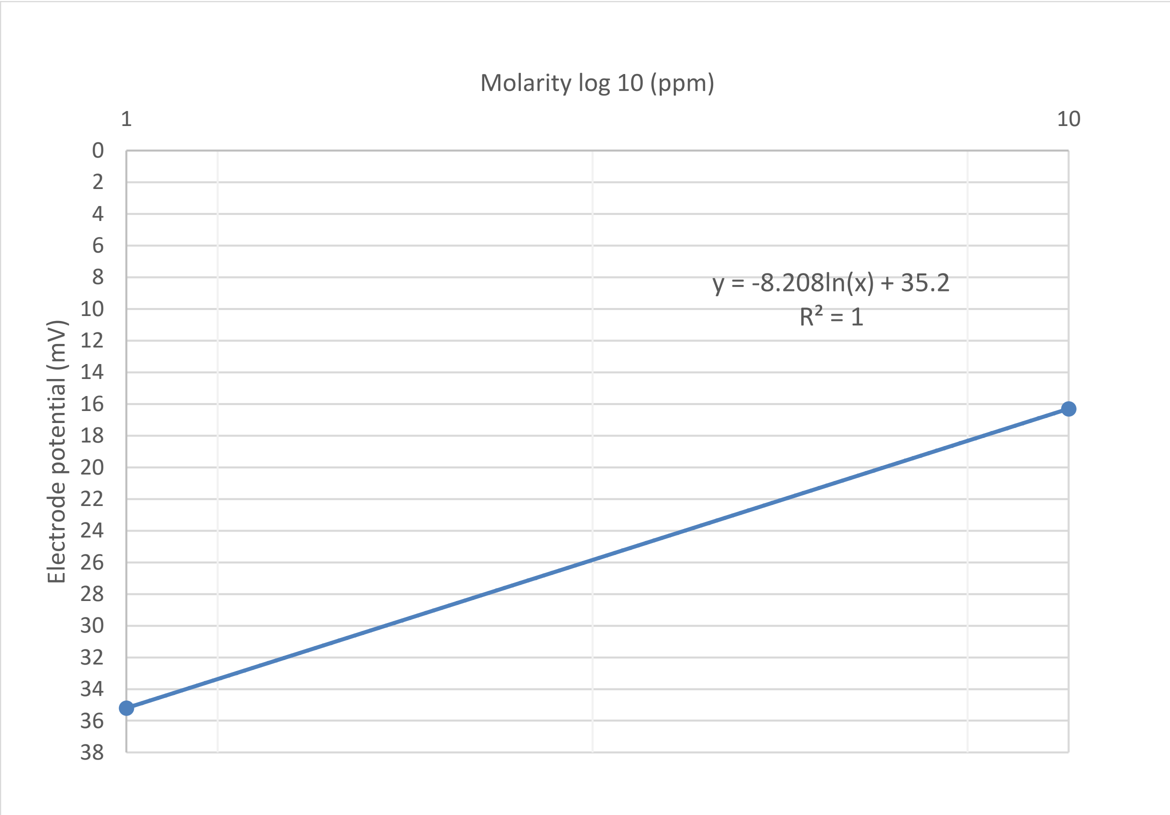


Figure 47: Calibration curve for chloride probe using 1ppm and 10ppm standards.

4.5.1.7.2 Nitrate content measurement

The method for nitrate concentration is similar to the chloride method above (NICO 2000 2016b).

- -Ion selective electrode for nitrate ion (ELIT 8021) is calibrated using a series of known standard solutions ($NaNO_3$).
- -Prepare four standard solutions of $NaNO_3$ (1ppm, 10ppm, 100ppm, 1000ppm).
- -For initial calibration submerge the probe in 1000ppm overnight.
- -Add 2mls of buffer (2M $(NH_4)_2SO_4$) to each standard solution, attach reference electrode (double junction lithium acetate ELIT 003), measure solutions and plot calibration curve (figure 48).
- -Weigh 50g of air dried soil and disperse in 100ml of deionised water for one hour, stirring occasionally.
- -Allow the insoluble residue to settle, then take 50mls of solution and add 1ml of buffer, stir well and take measurement.

The same calculation applied to the chloride probe to convert mV to ppm to mg/kg is applicable to the nitrate probe. As the results obtained are in the range of 1-1000ppm a complete calibration curve was utilised.

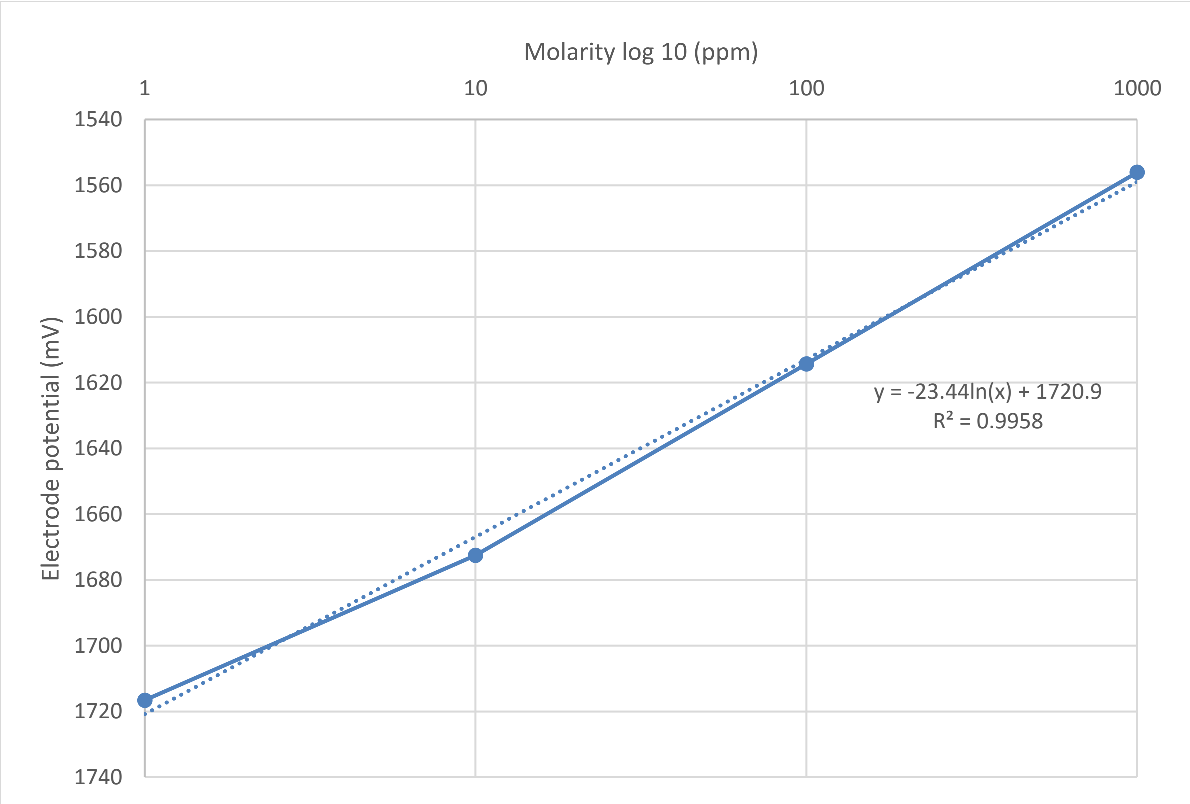


Figure 48: Calibration curve for nitrate probe.

4.5.2 Composition analysis

The preservation of materials in the ground can be affected by their composition as well as their burial environment. In order to assess any variation in composition and to analyse any correlation with the condition of objects, X-ray Fluorescence was carried out on a sample of bullets from each of the three cases study sites. 79 bullets were analysed in total. As stated in the introduction (section 1.3), one aim of this project is to examine whether the lead content and presence of impurities has an impact on the preservation of lead bullets. X-ray Diffraction was also carried out on a select number of bullets to analyse what corrosion compounds have formed on the surface of bullets and whether this has formed a protective barrier for the underlying metal. A theoretical background to XRF and XRD as well as their limitations is provided in appendix III.

4.5.2.1 Sample preparation and method

For this study a Bruker handheld XRF spectrometer (Tracer IV) was used for all composition analysis (Figure 49). All samples were run using a 'standard alloy' programme with a running time of 60 seconds.

As patination can affect the results of internal composition, bullets were prepared by first lightly brushing the surfaces and then using a scalpel to scrape a small area of the surface of the bullet (c.10mm²) until the underlying metal surface was reached. The bullet was then smoothed down with 320 grit sandpaper to create a smooth surface for the XRF measurements (figure 50). Little previous analysis has been carried out on lead bullet composition, but the preparation of the surface using this method is standard practice (Seibert *et al.* 2016, 145; Sivilich and Seibert 2016, 8). Removing the surface patina also allowed analysis into whether the surface composition is indicative of the metal core composition, which will be useful for decision making when analysing bullet collections in future. For each sampled bullet, initially three measurements were taken from the scraped area and three measurements were taken from the patinated surface initially to compare results. Edwards states that the lead content will be less abundant in the corrosion products than the lead core itself due to leaching of the metal (Edwards 1991, 65).

After confirming this through experimentation it was decided that analysis was conducted on the results from the scraped area where the lead core was exposed. On average there was a 2.98±4.95% difference in lead percent between measurements from the core and the patina of the bullets. As the readings taken from the scraped area of the core of bullets will give a more accurate composition of the metal, the current analysis is taken from core readings only.

X-ray Diffraction was performed using a Bruker D2 Phaser using Cu Kα radiation at a wavelength of 1.54184 Å. The diffractometer scanned 5° to 100° and recorded in 2θ. 22 of the bullets that were also analysed using X-ray Fluorescence were sampled using XRD to identify the types of corrosion products that had formed on bullets from each site. An area of the bullet surface was carefully scraped using a scalpel and the compound powder was collected. The powder was ground with a pestle and mortar and flattened onto a slide for placing into the D2 Phaser. Initially 20 minute and 1 hour runs were performed, but the spectra produced were not clear enough so all samples were run for 2 hours to create more defined peaks. Results were compared to standard compounds downloaded from the National Chemical Database Service (ICSD) which contains over 160,000 inorganic and related crystal structures *(Royal Society of Chemistry 2017)*. Appendix IV presents the main lead and tin compounds and their spectra used for reference in this study (Selwyn 2004).

Figure 49: Bruker handheld XRF spectrometer (Tracer IV), University of Huddersfield.

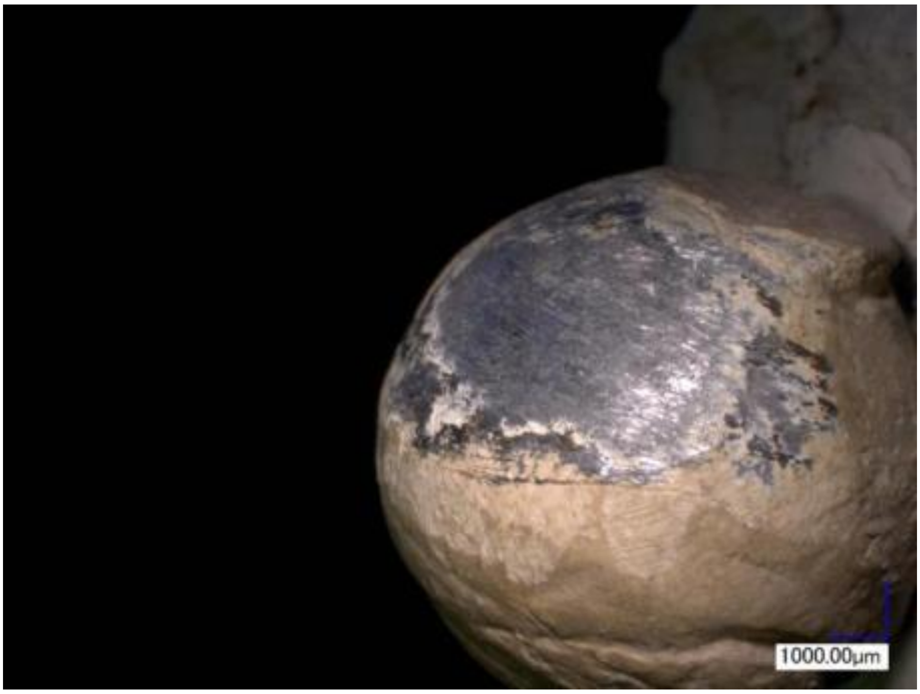


Figure 50: Example of a bullet smoothed, scraped and prepared for analysis.

4.5.2.2 Issues with lead bullet composition analysis

Several difficulties arise when analysing samples from lead bullet collections. Firstly, portable X-ray Fluorescence (pXRF) works best when the sample is flat (Pollard 1985, 27; Shugar and Mass 2012, 19). The spherical nature of the bullets made analysis problematic. The window on the pXRF measures 10mmx9mm which means that any area sitting within the window that is not covered by the object's surface would also be measured. Some bullets of smaller calibre, particularly pistol shot, did not fully cover the window. An attempt to rectify this problem was to print a 3D mount out of Acrylonitrile butadiene styrene (ABS), using a Cube personal 3D printer (3D Systems), courtesy of Aimee Hopper, PhD researcher. This was to ensure that not only the bullet would be kept steady, but the window size could be reduced and less of the object would have to be scraped (figure 51). This experiment proved unsuccessful as the machine had to be put in 'standard alloy' mode to read the metal composition of the bullet, but also read the plastic covering the remaining window, which was measured as predominantly 'titanium'; clearly inaccurate. There is potential to develop a method of covering part of the XRF window with a neutral material so as to reduce the damage inflicted on the artefacts, but for this study measurements continued to be carried out by removing a small area of the bullet surface area. This was necessary for collecting corrosion products as powders to later carry out X-ray diffraction (XRD) to examine the formation of corrosion products.

Several issues can also arise when analysing an XRF spectrum. For any object containing elements heavier than aluminium, the X-rays produced from the tube will interact with the sample and emit readings; this often happens for the elements Rh, W, Ag, and Pd (Shugar and Mass 2012, 32; Allen 2016, 42). Some bombarding X-rays may strike the object and not produce any fluorescence and so are deflected. This is a *Rayleigh* scatter, which is then collected by the detector and appear in the spectrum as elements present in the X-ray tube's anode. Bombarding X-rays may also give up part of their energies to the electrons in the sample, but not enough to cause fluorescence; this loss of energy is termed *Compton* scatter (Shugar and Mass 2012, 32).

Sum peaks may also occur when two fluorescent X-rays arrive at the detector at the same time and appear as a single X-ray at twice the photon energy. Silicon (Si) escape peaks may also occur from X-rays from the sample hitting the detector and the silicon present fluoresces, reducing the X-rays by the energy of the silicon Kα X-ray (E=E-1.74KeV). It is useful to check strongly emitting elements for Si escape peaks when interpreting XRF spectra (Shugar and Mass 2012, 33).

For the XRD results, data was compared to 2θ spectra of common compounds laid out in appendix IV. All major elements were identified, though some trace elements may have been missed during analysis.

Figure 51: 3D mount to hold lead bullets in position, made from Acrylonitrile Butadiene Styrene (ABS).

5 Moreton Corbet siege site

5.1 Introduction

Moreton Corbet is a 13th century stone-built castle lying 8 miles northeast of Shrewsbury. It was established as a small Royalist garrison, which came under siege and was captured by the Parliamentarians in 1644 during the Civil War, with as little as 10 Parliamentarians against a garrison of over 100 men (Harwood 2006, 37). The castle is Grade I listed and the structure, with its surrounding earthworks, is scheduled under the Ancient Monuments and Archaeological Areas Act 1979. However, the surrounding landscape where fighting took place is not scheduled and is not a registered battlefield. The fields surrounding the castle are littered with material from the 17th-century conflict which forms the main physical evidence of the siege, as well as impact scars left on the castle walls.

An ongoing metal detecting survey is being carried out at the site as part of PhD research at the University of Huddersfield which began in 2013. Fields surrounding the castle are being detected in 2.5 metre transects in non-ferrous mode to avoid modern iron material (Leese Pers. Comm. 05.06.2017). By the spring of 2017 approximately 200 lead bullets had been recovered and catalogued from the fields.

This site was chosen as a case study for analysing the condition of lead bullets in the ploughsoil as it allowed objects to be seen immediately after their recovery from the ground, without having to take into account the effects of long term storage. The condition of artefacts from the site were already known to be quite varied, from good to poor and so an investigation seemed appropriate into possible reasons behind the varied condition of objects.

The location of objects was recorded using GPS accurate to the nearest 0.60m and placed in clear plastic bags with individual ID numbers. They were washed immediately after returning to the university using a soft toothbrush and tap water, air dried and kept in airtight boxes with silica gel and humidity strips at a relative humidity <40% as advised by standard procedures (Rimmer *et al.* 2013, 13). The objects have been recovered from an area roughly 0.5km² over three agricultural fields and so is a manageable research area for spatial analysis (figure 52).

The following sections will present the results of the assessment of the historic landscape of Moreton Corbet, the assessment of the condition of lead bullets from the site, and analyse the soils data collected in the field. These datasets will then be discussed for each field in turn to explore the nature of each field and the preservation of material at the site.

5.2 Landscape

Moreton Corbet lies on low lying ground in the valley of the River Roden. The area predominantly comprises free draining sands and gravels with areas of boulder clays to the north and south. The boundaries of texture classes can be viewed in figure 53, revealing that the majority of the lead bullets retrieved from the site lie in areas of sands and gravels (Cranfield University 2016; Ordnance Survey of Great Britain 1967). The area has a mild climate and moderate rainfall with average annual rainfall of 659.9mm (Met Office 2017). The area under investigation has a fairly low lying topography containing a steep scarp to the east and south of the castle. Height above sea level ranges across the site from 63-70m AOD. The highest point lies to the west of the castle sitting at 69.50m AOD, which drops to 66m over a distance of 150m to the east (figure 54).

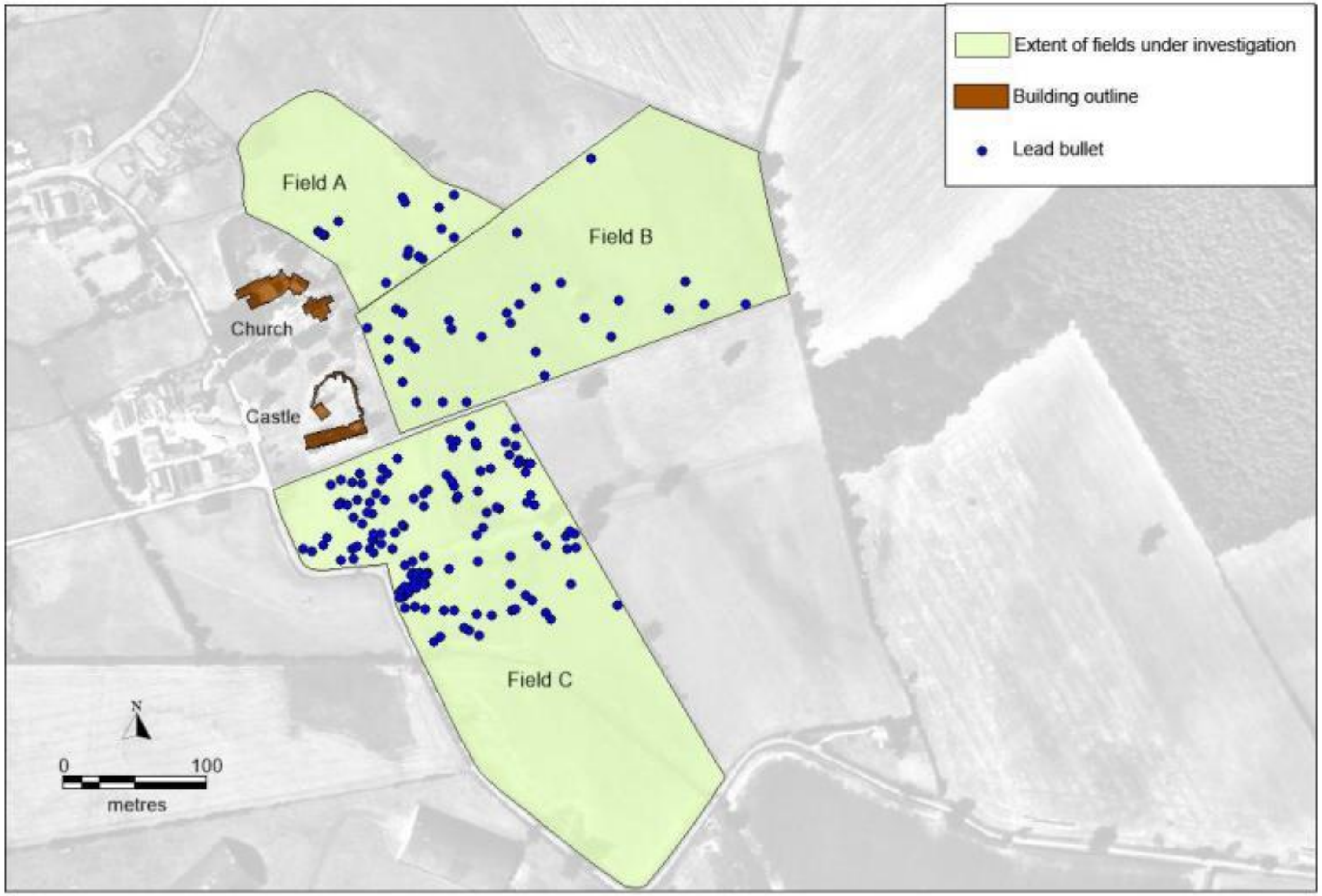


Figure 52: Map of Moreton Corbet showing extent of three fields under investigation (A, B, C) with the location of all recorded lead bullets (as of spring 2017). The detecting survey did not cover areas to the north of Field A, the far east of Field B, and the south of Field C. Base map Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. Base aerial photograph ©Cartographical Services 1983.

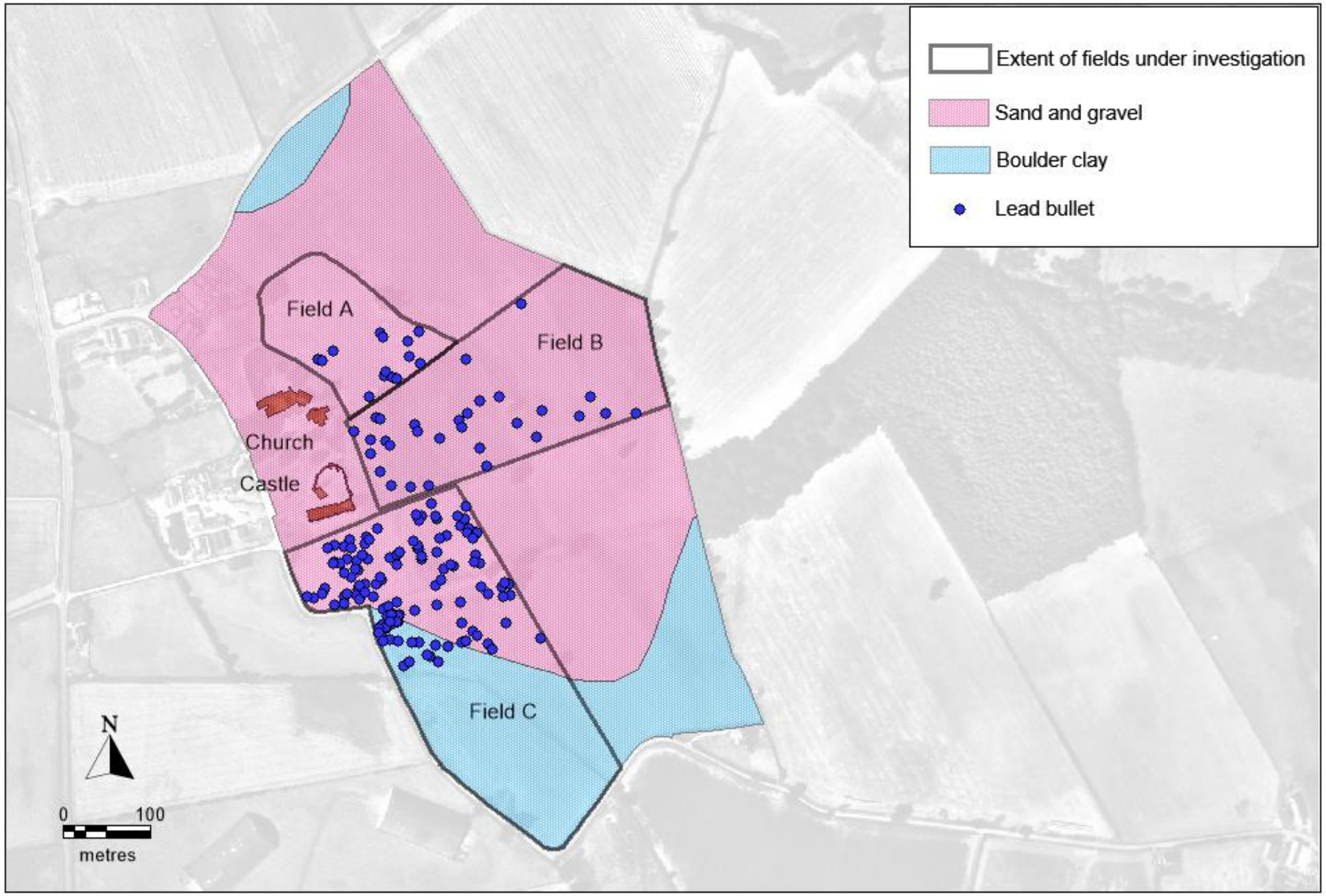


Figure 53: Superficial geology of area surrounding Moreton Corbet. Adapted from Geological Survey of Great Britain (Ordnance Survey of Great Britain 1967). Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. Aerial photograph © Cartographic services 1983.

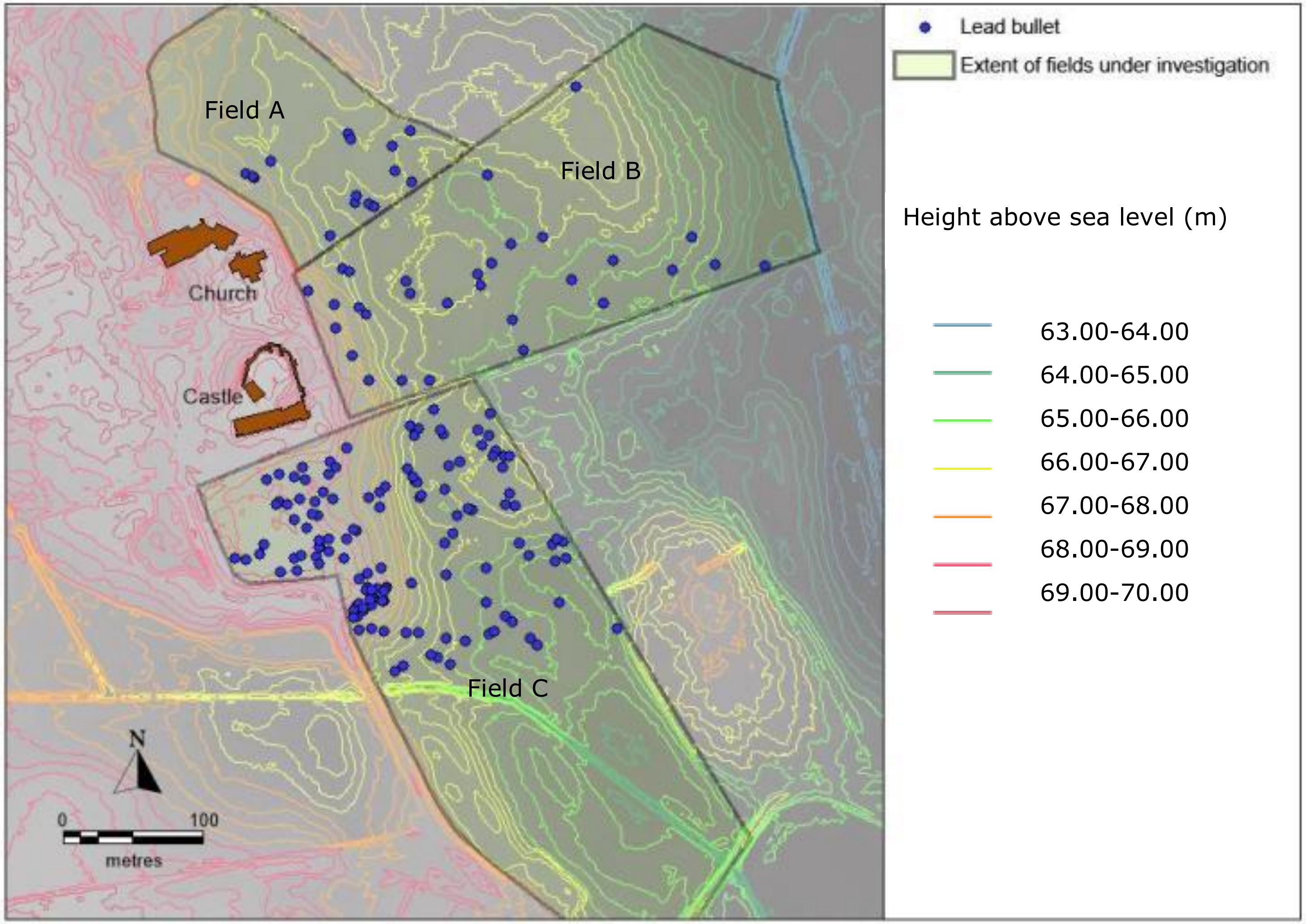


Figure 54: Contours (0.25m) across Moreton Corbet highlighting high ground to west and steep scarp down to east in fields B and C. ©LIDAR provided by data.gov.uk (Environment Agency 2018). Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service.

5.3 Field Methodology

Initial fieldwork at the site was carried out in October 2015 and June 2016 to assess the landscape and to take initial soil samples near to known artefact locations in order to assess general soil characteristics. The landowner was also interviewed for details on how the fields have been utilised over the last few decades, the results of which have been incorporated into the land use history assessment (section 5.4).

Pilot soil sampling at this site originally consisted of eight test pits close to the find spots of lead bullets in order to broadly assess the variation in physical and chemical properties of the soil across the site. Sections of turf measuring 0.30mx0.30m were removed by spade down to ploughsoil depth and lower soil samples were extracted using an auger. Each sample was taken from a distinct stratigraphic layer and bagged and labelled separately. Depending on the conditions and weather, samples were taken from maximum depths of 0.60-0.90m. Topsoil depths averaged at 0.28m, subsoil averaged at 0.44m and lower subsoil deposits averaged at 0.70m.

After initial landscape assessment and soil sampling had taken place, it was revealed that samples varied in pH, conductivity, water content and texture, and so it was deemed necessary to expand the sampling procedure utilising a more intensive and systematic method. Initial sampling did not cover enough of the different topographical areas present in the fields; for instance, no sample was collected from the steep slope in Field C and only one or two samples were collected from each area which did not provide a range of samples for comparison. There were also clusters of bullets in the landscape that were not represented by a soil sample and so further samples were required.

A revised methodology of soil sampling was instigated in April 2017; 22 further test pits were dug across the site in a roughly herringbone pattern to gain better coverage of the fields whilst also avoiding spring crop growth (figure 55). The herringbone approach to sampling has been shown to be the optimal approach when little information is available on the spatial distribution of data required (Ferguson 1992). Systematic sampling allowed the identification of zones in the landscape which exhibited similar levels of soil attributes. These zones can be seen in the landscape based on topography and slope, but are confirmed by soil analysis and historic land use assessment. Section 5.8 assesses the zones and their attributes in more detail.

Sampling focused on characterising Field C as 78% of the bullets were retrieved from this field (table 29). Further samples were collected from Field B to characterise the strip of land to the east of the castle which was formerly a grassed track way and has a distinct history of land use. Samples were collected in very dry sunny conditions with no rainfall for the preceding two weeks. This means that the soil water content may be lower than average for the time of year. The 2017 soil samples were extracted using a gouge auger. Due to the narrowness of the auger three samples were taken from each location and amalgamated together in bags to form a sample of roughly 500g for laboratory analysis.

Field	**Number of bullets retrieved**	**Percentage of collection**
A	17	10%
B	30	17%
C	130	78%

Table 29: Percentage of bullet assemblage retrieved from each field at Moreton Corbet.

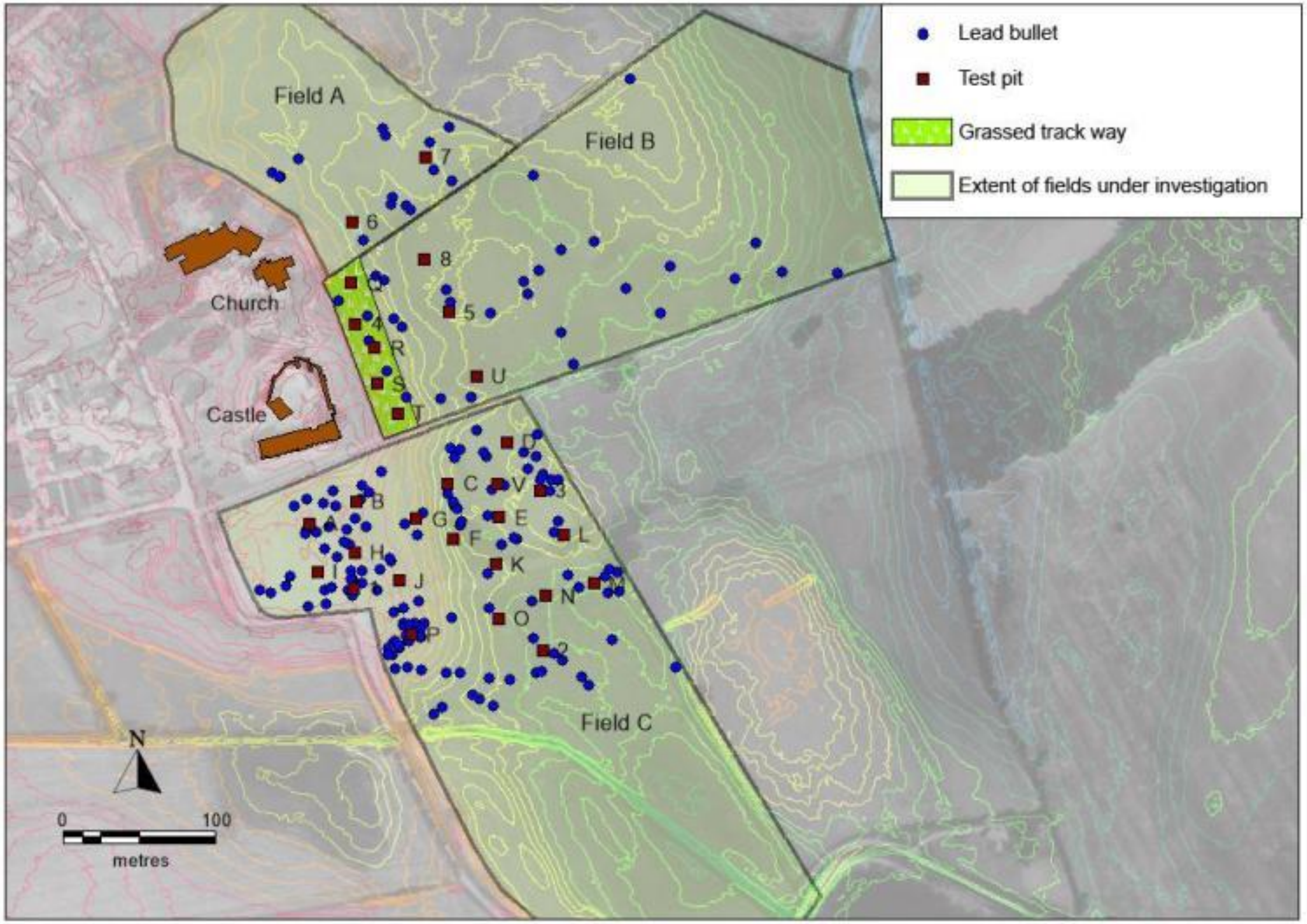


Figure 55: Location of all 30 test pits sampled at Moreton Corbet (1-8 initial sampling and A-V herringbone sampling). ©LIDAR provided by data.gov.uk (Environment Agency 2018). Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. Aerial photograph ©Cartographical Services 1983.

5.4 Historic Landscape assessment

A land use assessment was carried out at Moreton Corbet to establish how the fields have been utilised over the past three centuries. The priority was to identify when the three fields under investigation were in pasture and when they were under arable cultivation in order to assess how long the fields have been under the plough. More data is available from the post 1930s due to the availability of aerial photographs from the Second World War onwards. Table 30 summarises the land use history of each field, whilst table 31 gives detail of each field by period, referencing maps and aerial photographs analysed. The fields have predominantly been in use as grassland until a change to arable cultivation in the early 1980s. Sources include aerial photographs held by Shropshire Archives and Historic England Archive, Swindon.

Field	**Land use**
A	Grassland/meadow until change to arable between 1992 and 1995, but remains predominantly in use as grassland/grazing. Currently pasture.
B	Grassland/meadow until change to arable between 1975 and 1983, which then becomes almost in constant arable use with piggeries. Currently cereal arable.
C	Castle gardens/grassland/meadow until change to arable between 1974 and 1983, which then becomes almost in constant arable use, with piggeries in western corner every few years. Currently cereal arable.

Table 30: Land use summary for the three main fields at Moreton Corbet.

Land use Field A	Land use Field B	Land use Field C	Source (maps and aerial photographs)	Date
Glebe/meadow	Meadow	Castle gardens/grass	18th century estate map (SRO Map 2609/1 Estate map of Robert Kynaston, Moreton Corbet and Shawbury Undated)	undated
Grassland	Grassland	Grassland	Tithe map (Tithe apportionment of Moreton Corbet (parish), Shropshire. IR 29/29/225 1838)	1838
Grassland	Grassland	Grassland	Land Utilisation survey of Britain, Wolverhampton sheet 61 (Ordnance Survey of England and Wales 1938) (Aerial photograph SJ 5623/5 118 126 1938)	1938
Grassland	Grassland	Grassland	(Aerial photograph RAF MSO 31076/PO-K 10876 1940) (Aerial photograph RAF CPE/UK 201, 3351 1947)	1940-1947
Grassland	Grassland	Grassland	(Aerial photograph RAF/58/5171 291 1962)	1962
Grassland	Grassland	Grassland	(Aerial photograph SJ 5623/3 118 126 1975) (Aerial photograph WAB 800/4 1974)	1974-1975
Grassland	East end arable West end grass	Arable	(Cartographical Services Ltd 1983)	1983
Grassland	Arable	Arable	(Aerial photograph CPT 14922/478-479 SJ5623/6 1992)	1992
Arable (?)	Arable	East end arable West end pigs	(Aerial photograph CPT 16296/080-081 SJ5623/8-9 1995)	1995
Arable	East end pigs West end arable	East end arable West end pigs	(UK Perspectives 1999)	1999
Grassland	Arable	East end arable West end pigs	(Aerial photograph NMR 24315/14 SJ 5623/19 2006)	2006

Grassland	Arable	East end arable West end pigs	(Digital aerial photograph SA0703-013 2007)	2007
Grassland	Arable	East end arable West end pigs	(Digital aerial photograph SA808-060 2008)	2008
Grassland	Arable	Arable	(Get Mapping plc 2010)	2010
Grassland	East end pigs West end arable	Arable	(Get Mapping plc 2012)	2012
Grassland	Arable	Arable	Field observations	2014-2017

Table 31: Historic land use of Fields A, B and C with referenced sources.

5.4.1 18th-century landscape

The earliest remains at Moreton Corbet date to around AD1200 when the castle was established (Newman and Pevsner 2006, 412). The castle was remodelled and converted into a country house in the 16th century. It was fortified in the Civil War, was besieged at least twice, and restored after the war. The Parliamentarians took hold of the property in 1644, and after falling into a period of disuse it was finally abandoned in the 1680s (Harwood 2006).

As shown by the earliest map of the estate from the mid 18th century (SRO Map 2609/1 Estate map of Robert Kynaston, Moreton Corbet and Shawbury Undated), the field boundaries across the site have changed significantly. The area known as 'Castle Court' comprises the main area of the castle and adjoining formal gardens which were developed in the 16th century when the south range was built in 1579 to obtain southern views of the grounds (Weaver 1981). Remodelling consisted of an extensive garden to the south of the castle and an entranceway and gardens to the west which is now in a scheduled area (figure 55). The gardens to the south of the castle which now forms part of Field C was surveyed in the 1980s, revealing a square platform as a formal garden plateau of approx. 130m², extending south and west across the modern road line (Historic England 1981). This eastern garden terrace boundary is present as a crop mark on the 1983 aerial photograph (Cartographical Services Ltd 1983) and signifies the edge of the garden plateau residing right on the edge of the top of the natural slope in Field C. A mound to the south west of the garden area, now in a separate field, is included in the scheduling of the site. The gardens are cut by the road on the west and south sides. During the 18th century the fields were in use as meadows and formal gardens. A 1938 oblique aerial photograph shows faint traces of surviving ridge and furrow in Field B, indicating that it had not been intensively cultivated between the period of the gardens being established in the 16th century and the early 20th century (Aerial photograph SJ 561231 1938).

The name 'Moreton' refers to a farmstead in or near a fen or moor (Ekwall 1960, 331). The 18th-century estate map identifies several field names relating to the wet nature of the land to the south and east of the village. Fields in the vicinity of the castle include 'Pool Meadow', 'Dipmoor Meadow', 'Pond Meadow', and 'Moor' indicating that the area was predominantly marshy and contained water features. Both fields A and C reside in areas labelled as 'moor' (figure 56).

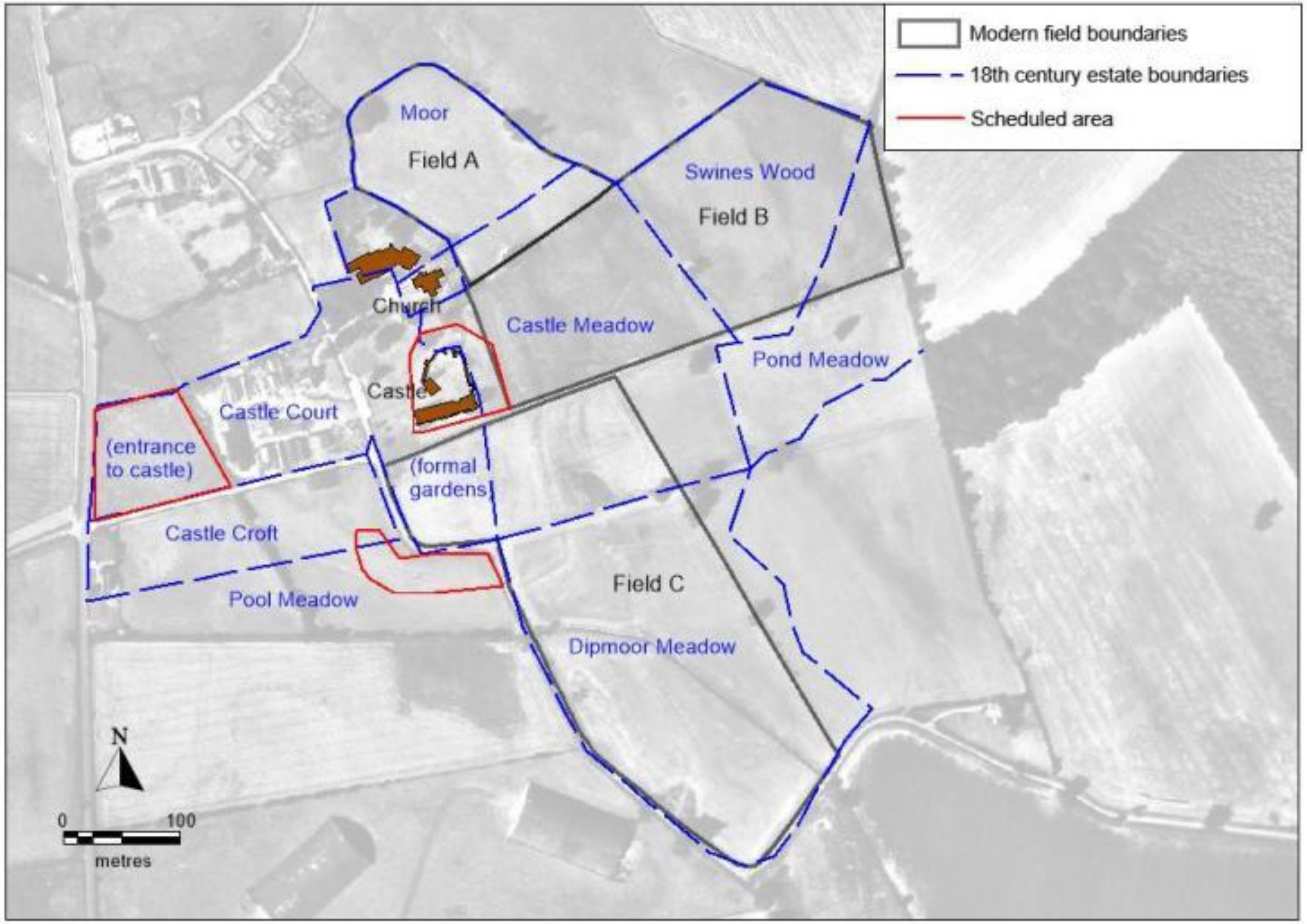


Figure 56: Map of Moreton Corbet showing current field extents overlaid with 18th-century field boundaries and field names (in blue). Note that the 18th-century estate map is not accurate to OS standard and thus boundaries are an approximation. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. Aerial photograph ©Cartographical Services 1983.

5.4.2 19th-century landscape

The 1838 tithe map shows further details of the site and changes in field boundaries (Tithe apportionment of Moreton Corbet (parish), Shropshire. IR 29/29/225 1838). The majority of field boundaries remain similar to the 18th-century, though the modern road line is now present to the west and south of the castle running through the former formal gardens. The boundary of Field A remains as it appears on the tithe map until the present day indicating very little change to this field (figure 57).

There are changes around the vicinity of the castle. Most significantly, a north to south linear feature to the east of the castle is now depicted. This feature appears to be a wide (c.6m) ditched feature that continues southwards through fields B and C. This feature is visible as a crop mark on 1947 and 1983 aerial photographs (Cartographical Services Ltd 1983; RAF aerial vertical CPE/UK 1926 2094 1947) and appears to turn to the west at its southern end forming a sharp corner, though this corner is not recorded on any maps. It appears to join up with part of the surviving mound and platform scheduled as part of the formal gardens south west of the castle (figure 57). It appears likely that this curving linear feature is a garden terrace feature forming part of the formal garden earthworks developed in the 16th century (highlighted in yellow, figure 57). It lies in the middle of the natural scarp dividing the garden plateau from the area down slope to the east.

The tithe map also identifies water features present in the landscape. To the east of the castle lies a regular-shaped pond or lake which is likely to be a formal garden feature. This feature is still present but overgrown in 1975 and completely lost by 1983 (Aerial photograph SJ 5623/3 118 126 1975; Cartographical Services Ltd 1983). There also appears to be a channel running from the garden terrace feature to the corner of the lake, identified on a 1938 oblique aerial photograph (Aerial photograph SJ 5623/5 118 126 1938). It is possible that by this point the features have been drained, but used to be filled with water forming garden water features or an outer moat to the castle. To the west of the castle a drain or stream is also noted on the tithe map running through part of the garden area and former entranceway to the castle (figure 57).

By the 1st edition Ordnance Survey of 1884 several boundaries have been lost and the area under investigation consists of three moderate sized fields (Ordnance Survey of England and Wales 1884). Part of the ornamental lake is still present, though it has reduced in size. The line of the sluice stream is also now present running in a north west to south east direction through Field C which may indicate the start of drainage management in the area (figure 58). The boundaries of the terracing identified on the tithe map are no longer mapped, though a footpath running through the southern fields is now present, which is moved southwards by 1902, suggesting the fields are in open meadow use with public access (Ordnance Survey of England and Wales 1902).

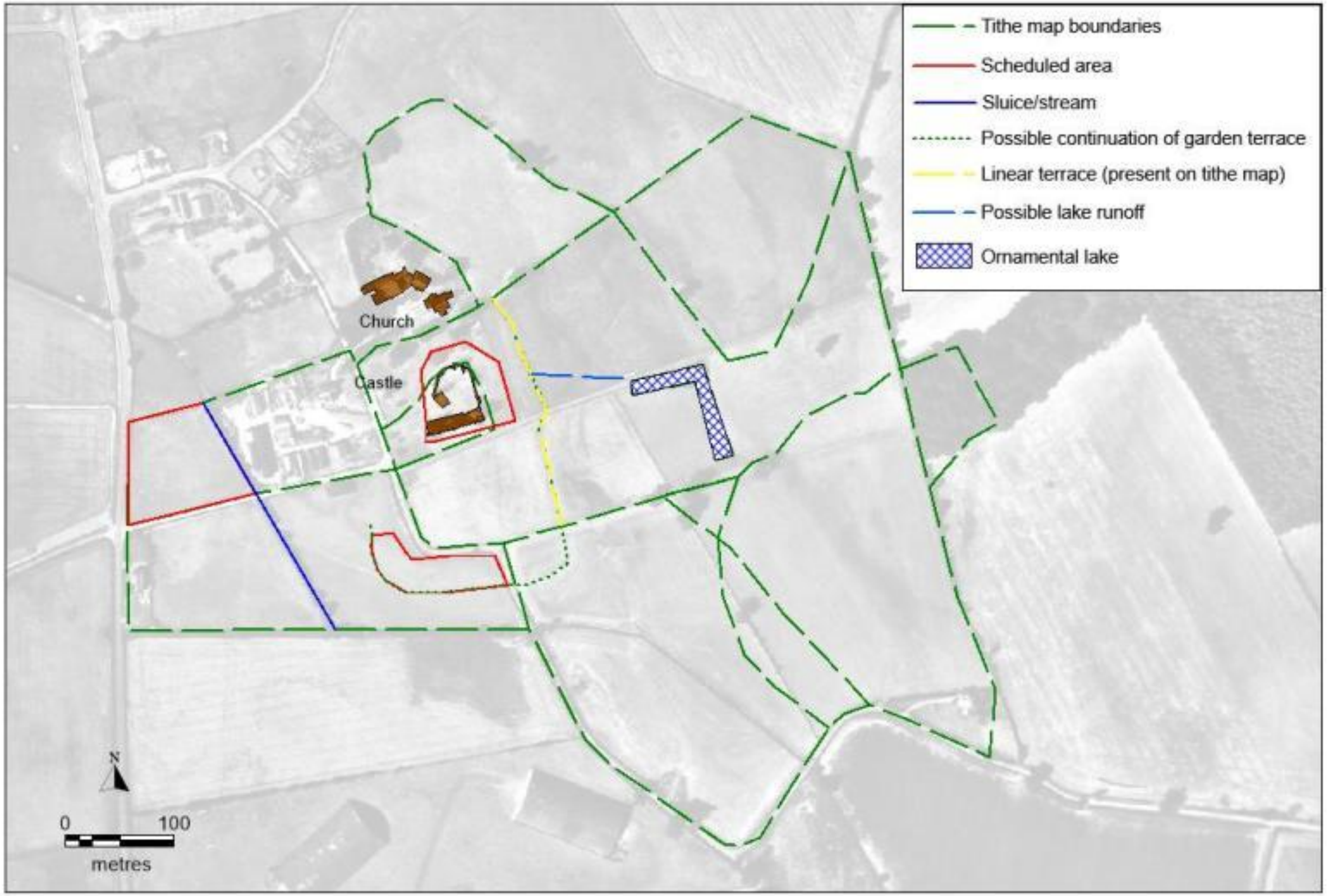


Figure 57: Map of Moreton Corbet showing 1838 tithe map boundaries and garden 'terrace' in yellow (Tithe apportionment of Moreton Corbet (parish), Shropshire. IR 29/29/225 1838). Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. Aerial photograph ©Cartographical Services 1983.

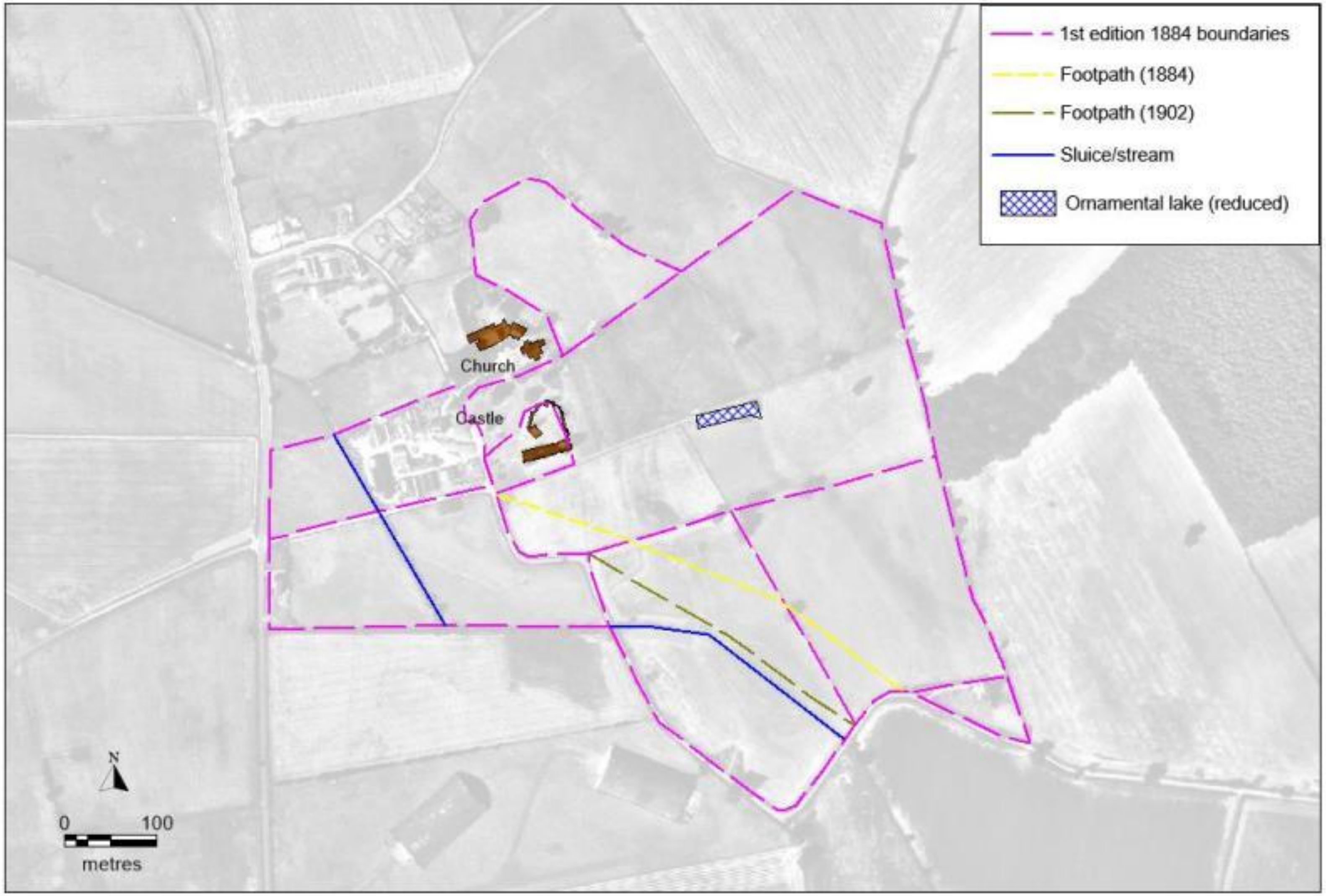


Figure 58: Map of Moreton Corbet showing 1884 1st edition boundaries (Ordnance Survey of England and Wales 1884, 1902). Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. Aerial photograph ©Cartographical Services 1983.

5.4.3 20th-century to present day landscape

In 1938 all the fields under investigation in this research continue to be under permanent grassland/meadow (Ordnance Survey of England and Wales 1938). However, 1938 oblique aerials show traces of cultivation crop marks to the east of the castle in Field B, so some cultivation must have taken place since the medieval period. This is likely to have occurred before the development of the estate gardens in the 16th century or soon after the estate was abandoned in the late 17th to early 18th century (Weaver 1981).

Field boundaries do not change between 1884 and 1947 (RAF aerial vertical CPE/UK 1926 2094 1947). However, by this time the airfield to the south of the estate has been built and a temporary road is now present running through the extent of the fields towards the air base to the south (figure 59). This road is still present partially as a parch mark on the 1962 aerial photographs, and by 1975 is visible in sections as a soil mark with rubble and an irregular patchy surface (Aerial photograph RAF/58/5171 291 1962; Aerial photograph SJ 5623/3 118 126 1975).

By the late 1970s to early 1980s field C had been converted to arable, as well as part of Field B. In the early 1970s the farmer owned a small dairy herd. However, to make the farm more profitable the dairy herd was sold in the late 1970s and replaced by arable crops and breeding pigs (Pinches Pers. Comm. 08.03.2018). This may also be partly due to Britain joining the EEC, now the EU, in 1973 and the incentive to convert more farmland to arable through the Common Agricultural Policy (CAP) of 1962.

By 1983 the central road running east to west through the fields under investigation is established, forming the current field boundary at the site separating Field B to the north and Field C to the south (figure 59). The 1983 aerial photograph of the site exhibits several features in the landscape from previous decades that can be seen as crop marks, including former boundaries visible on the tithe map of 1838 (Cartographical Services Ltd 1983). Also evident as an earthwork is the garden terraced bank skirting the east of the castle, running in a rough semi-circle through fields B and C. As shown by the contours this feature runs through the middle of the natural slope and continues westwards out of the area under investigation (figure 60).

Also present as crop marks are possible drainage channels in fields B and C which correspond to sketches of modern drainage channels supplied by the land owner. The 1983 aerial photograph also indicates a small naturally-formed pond at the base of the slope in Field C. As mentioned above, this landscape is historically boggy and though drainage has been carried out in the 19th and 20th centuries it is still prone to waterlogging even in mid-August when the aerial photograph was taken. By the 1990s the site corresponds with present day field boundaries, with some temporary boundaries in place for the separation of areas for pig farming (UK Perspectives 1999; Get Mapping plc 2010, 2012) (figure 61).

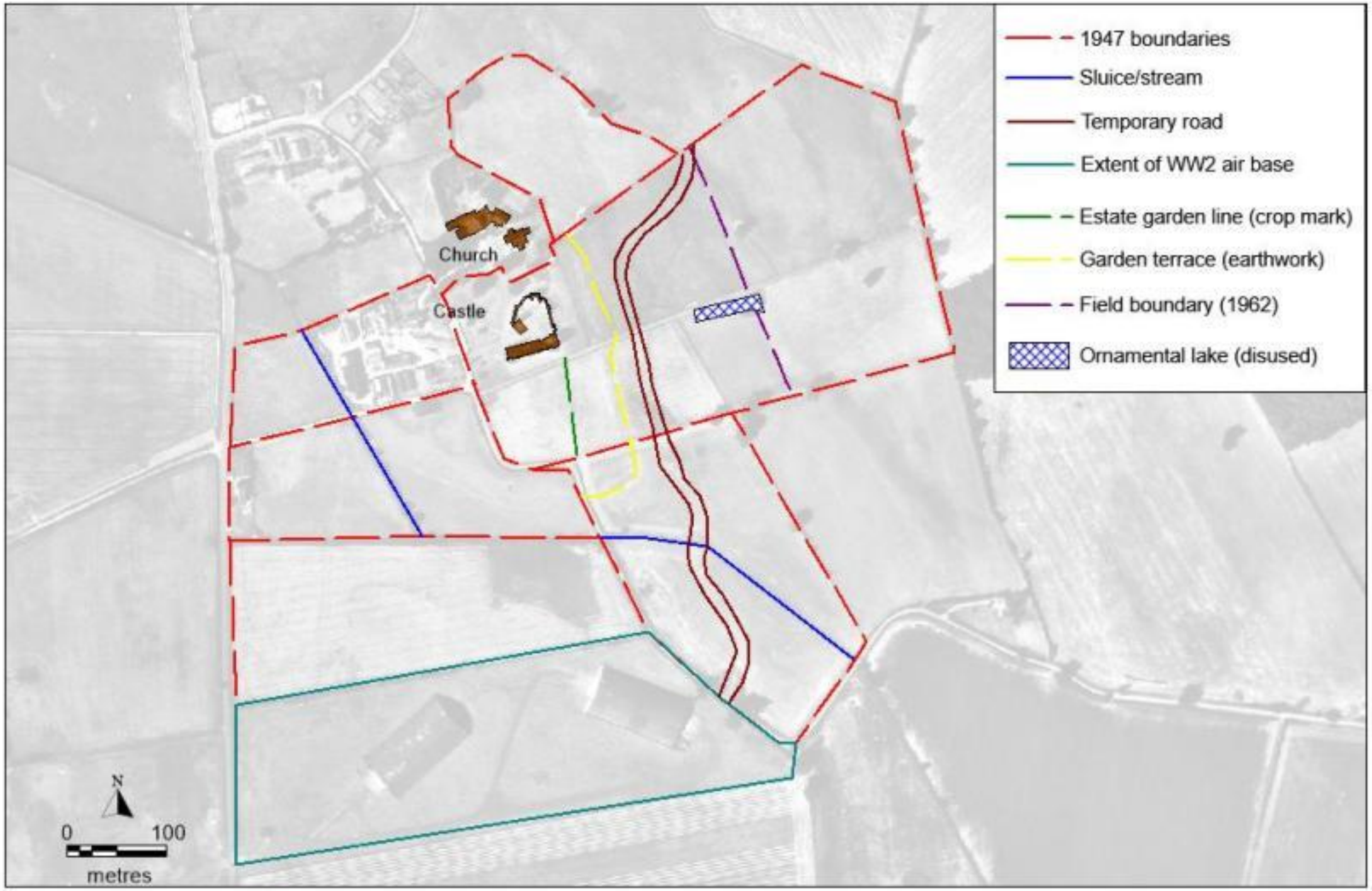


Figure 59: Map of Moreton Corbet showing 1947 and 1962 boundaries (RAF aerial vertical CPE/UK 1926 2094 1947; Aerial photograph RAF/58/5171 291 1962). Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. Aerial photograph ©Cartographical Services 1983.

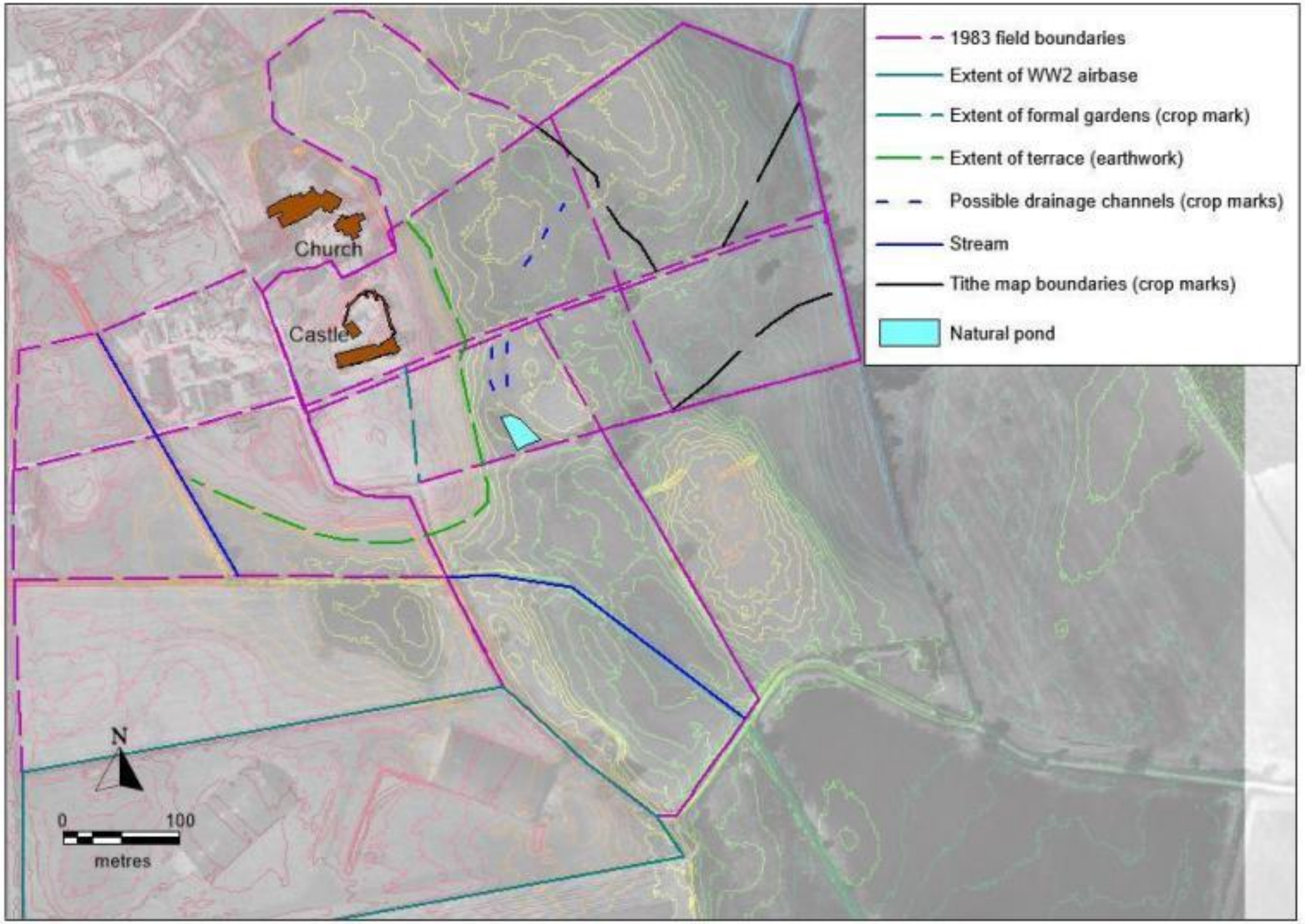


Figure 60: Map of Moreton Corbet showing 1983 boundaries and extent of garden terracing against contours (Cartographical Services Ltd 1983). Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. Aerial photograph ©Cartographical Services 1983. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

Figure 61: Map of Moreton Corbet showing 20th century modern field boundaries (UK Perspectives 1999; Get Mapping plc 2010, 2012). Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. Aerial photograph ©Cartographical Services 1983 ©LIDAR provided by data.gov.uk (Environment Agency 2018).

5.4.4 Moreton Corbet landscape

From the above discussion it is evident that the landscape at Moreton Corbet is very complex and numerous changes have occurred across the site since the medieval period. The site was occupied in the early 12th century as a small stronghold and the three fields investigated in this study have been under grass since at least the mid-18th century forming part of the estate and grounds of the castle. There was a change in land use in the 1980s when Fields B and C were brought under arable cultivation and partly used for pig farming, forming temporary field boundaries. These fields have remained in arable use for cereal crops until the present day. Fields B and C have been ploughed to a depth of c.0.25m and sub soiled every four years to a depth of 0.35m; a process by which a type of vertical plough is used to break up any soil compaction deep down in the soil profile without turning the soil over (Pinches Pers. Comm. 08.12.2014). Field A has been kept predominantly in pasture use apart from occasional cultivation in the 1990s. The strip of land directly to the east of the castle in Field B has been kept as a grassed track way and has only been incorporated into the cultivated field in 2014. This track lies to the east of the castle, upslope of the garden terrace feature running through the field identified on the tithe map, and though it does not reside at the same height of the former garden plateau in Field C, it is kept above the level where the site is prone to waterlogging (figure 62).

Features in the landscape at Moreton Corbet form topographical zones. The western corner of Field C to the south of the castle forms a flat plateau which was developed in the 16th century as part of the formal gardens of the castle. The boundary of the Court on the estate map defines the eastern extent of the plateau before the ground naturally slopes down to the east (figure 62). This plateau represents the highest point of the site and may have implications for the preservation of artefacts. The development of a garden and maintenance of the soil through the 17th century may have raised the soil level and potentially buried artefacts deposited at the site during the siege of 1644. The boundary identified on the tithe map lies mid way between the top and bottom of the natural slope in fields B and C. This area of higher ground may make bullets less vulnerable to decay as they are kept away from areas prone to waterlogging down slope. Significantly, the grassed track way to the east of the castle in Field B lies upslope on the edge of this terrace line. This area, as well as the garden plateau in Field C, is away from waterlogged areas down slope to the east.

Evidence has shown that Moreton Corbet village and castle reside on slightly raised ground in a predominantly wet landscape to the east and south. Evidence from the historic mapping and field observations suggest the groundwater table was and still is relatively high, with waterlogging occurring in low lying areas of the site. As shown in figure 62, zones prone to waterlogging, based on aerial photographic evidence, contour data, comments by the landowner and the author's field observations, reside in fields B and C at the lowest points of the site. While there has clearly been drainage in the last 150 years which will have reduced the water table, during soil sampling, several test pits taken in the waterlogged areas filled with water during excavation. This indicates that the level of the water table was approximately 0.60-0.70m depth in April 2017.

The landscape around Moreton Corbet village and castle is predominantly wet and due to its low lying nature it is unlikely to have been cultivated for long periods until the land was drained in early modern times. Features have been attempted to be identified in the landscape, though some need further investigation to positively define their nature, such as the potential terracing around the eastern edge of the castle. A specialist documentary study of medieval and early modern land use history to further investigate the development of the gardens and the cultivation of the site may be possible, but is beyond the scope of this current study. Nonetheless, several features and zones in the landscape have been identified. In section 5.8 the implications for the nature of the landscape and the condition of the bullets will be discussed for each field based on the zones identified through landscape analysis.

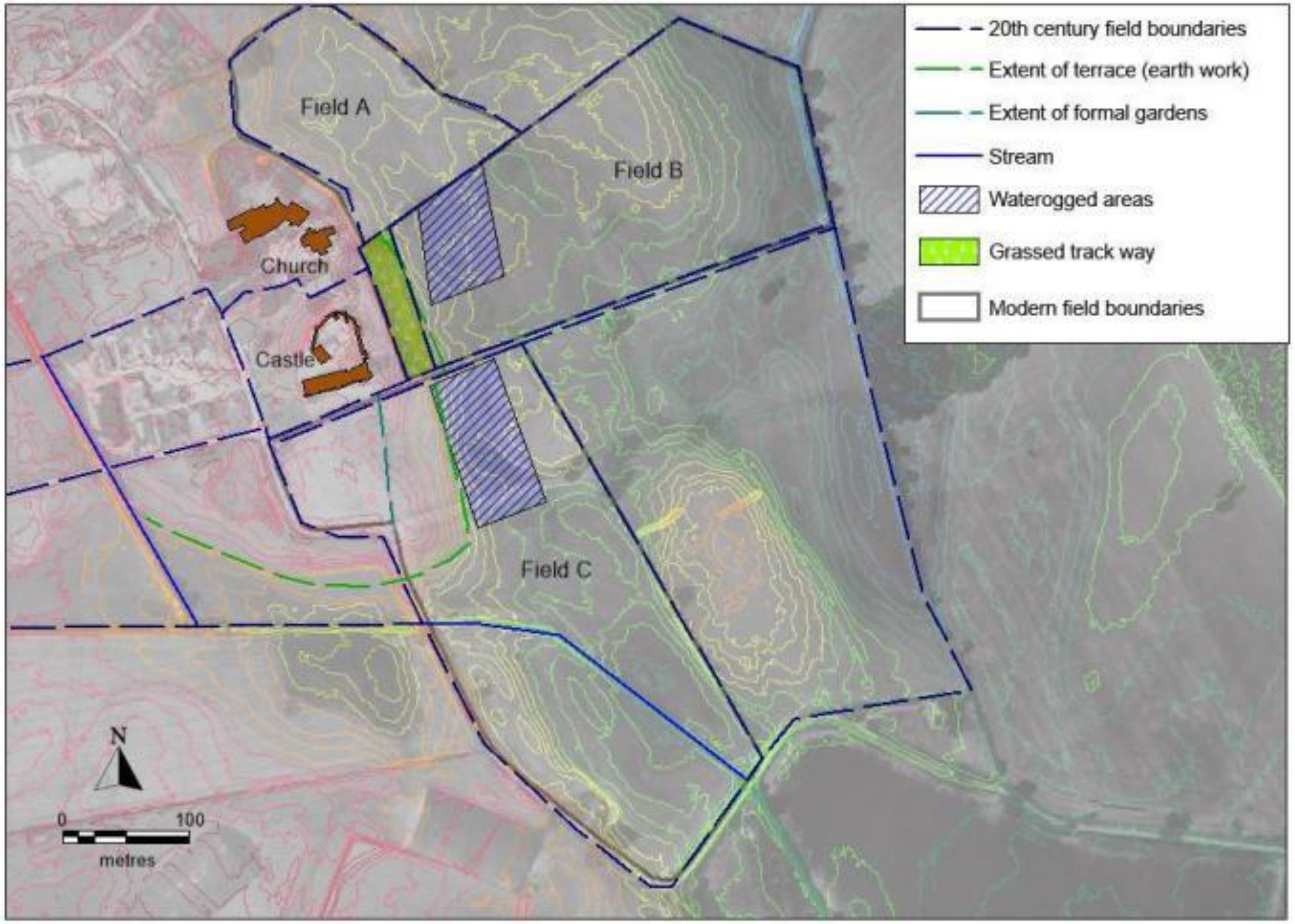


Figure 62: Map of Moreton Corbet identifying zones and features across the site. The grassed track way has not been cultivated until 2014. The edge of the garden plateau to the south is visible before the ground slopes down to the east towards areas of waterlogging. Based on comments from the landowner, field observations and previous water features on aerial photography (UK Perspectives 1999; Get Mapping plc 2010, 2012; Cartographical Services Ltd 1983). Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. Aerial photograph ©Cartographical Services 1983. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

5.5 Lead bullet condition assessment

177 bullets from Moreton Corbet were assessed for their condition using the methodology laid out in section 3.4 and appendix I. This equates to 89% of the total lead bullet collection from the site as of April 2017. As detecting surveys were still being carried out at the time of analysis, not all artefacts were available for examination. Each bullet was given a score for each of the five condition attributes and an overall condition score. It was also noted whether each bullet had any of the following: indications of being hit by a plough or spade; significant general pitting over the surface; significant areas of localised corrosion; significant eroded/abraded surface; cracks on the surface; or a powdery surface.

The majority of the bullets scored a 2 or 3 for being in overall good or fair condition (83%) (figure 63). Few bullets were deemed to be in very good or poor condition (11% and 6% respectively). When the scores of all five condition categories were totalled up for each bullet, the vast majority of bullets (85%) scored between 7 and 13 out of a possible total of 20, highlighting that few bullets were at either extreme of preservation (figure 64). An explanation of how overall condition score equates to the five condition score categories is presented in table 32.

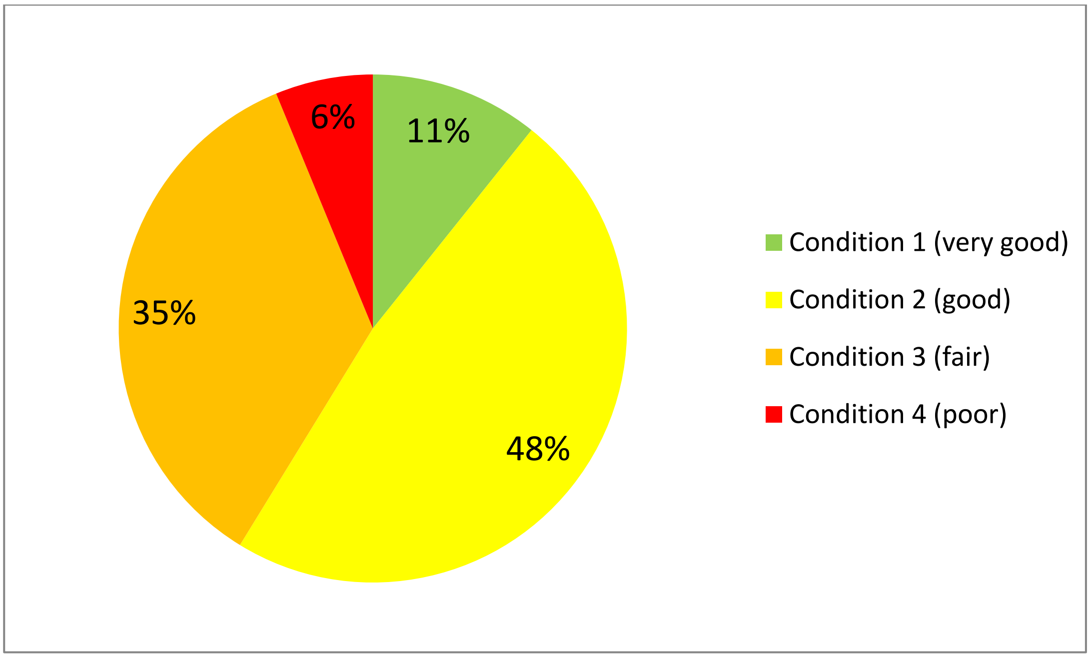


Figure 63: Overall condition of lead bullets from Moreton Corbet by total percentage of collection studied.

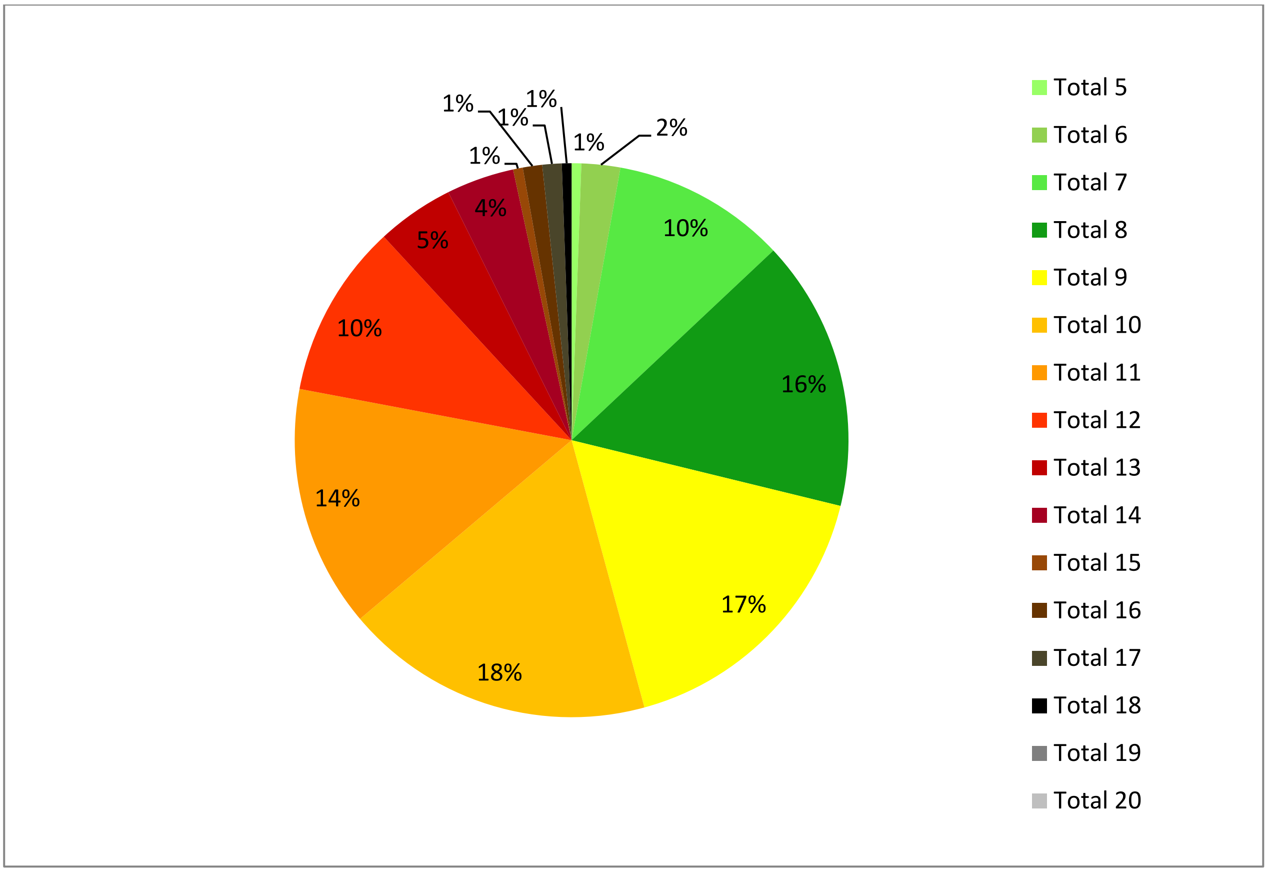


Figure 64: Total scores of lead bullets from the five condition categories (out of a possible 20) by total percentage of collection studied. The colours equate to the same scoring range as the overall condition score in figure 62.

Condition score	**Overall score of lead bullet condition (possible total of 4)**	**Total condition score from five condition categories (possible total of 5-20)**
Very good	1	5-7
Good	2	8-10
Fair	3	11-13
Poor	4	14+

Table 32: How the overall condition score equates to the total category condition score of lead bullets.

For each of the five separate condition categories, few bullets scored a 4 for poor condition in any category (figure 65). 98% of the collection scored a 1 or 2 for 'preservation of shape' indicating that their overall shape has not been damaged significantly from conditions in the ground. Comparing this data against the results of the other four categories suggests preservation of shape is not particularly insightful for lead bullets. This is due to the bullet's robust dense spherical shape making it less vulnerable to being hit or broken in the ground compared to other objects like brooches and pins which have a weaker shape and are prone to bending and snapping under pressure (Haldenby and Richards 2010).

The 'smoothness of surface' and 'stability of surface' categories are more indicative of condition and score higher than any other category. Over a third (36%) of the assemblage scored a 3 or 4 for stability of surface and 34% scored a 3 or 4 for smoothness of surface. Surface detail also scores quite high for conditions 3 and 4, suggesting that the condition of the bullets' surfaces is an issue at this site. Nevertheless, the majority of bullets still score a 2 for good condition in most categories, indicating that preservation is not excellent or extremely poor at this site.

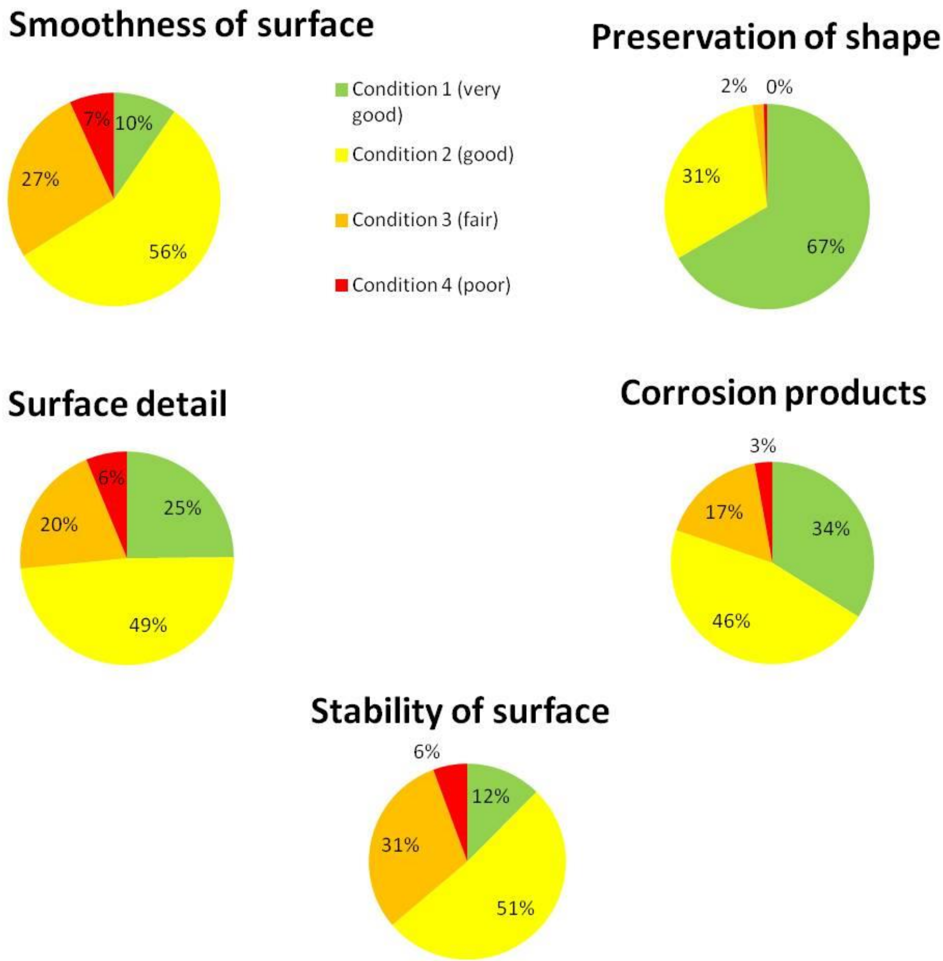


Figure 65: results of lead bullet scores for all five categories of condition assessment.

Further data was collected on certain corrosion attributes of the bullets, the results of which can be seen in table 33. Only five bullets were identified as being hit by a spade or plough, though this number is likely to be greater as it is very difficult to identify such evidence marks with certainty. More research into surface marks and experiments should be undertaken to address this problem of surface mark identification, some of which has been undertaken, but with a focus on use marks as opposed to post depositional marks (Parkman Unpublished).

Some 34% of the collection studied had evidence of significant localised corrosion in the form of pitting or intergranular corrosion; in some cases globules have formed on the surface of the bullets and some have fallen or broken off leaving scarring (figure 66). As discussed in section 3.3, localised corrosion on lead occurs when the passive corrosion layer does not cover the entire surface of the object or the patina has been compromised, forming weak points and leaving the underlying metal vulnerable to soluble ions in the soil solution to react with the metal (Edwards 1996). A handful of bullets are in particularly poor condition where areas of localised corrosion have developed and penetrated the surface patina allowing an uneven mineralised surface to form (figure 67).

Condition issue	Total number of bullets studied	Percentage of total collection studied
Hit by plough or spade	5	3%
General pitting issues	12	7%
Significant localised corrosion	60	34%
Significant eroded/abraded surface	61	34%
Significant cracks on surface	14	8%
Powdery surface	2	1%

Table 33: Total number of bullets in collection with corrosion characteristics.

Figure 66: Bullet with scars and pitting from localised corrosion attacks (MOR 0239).

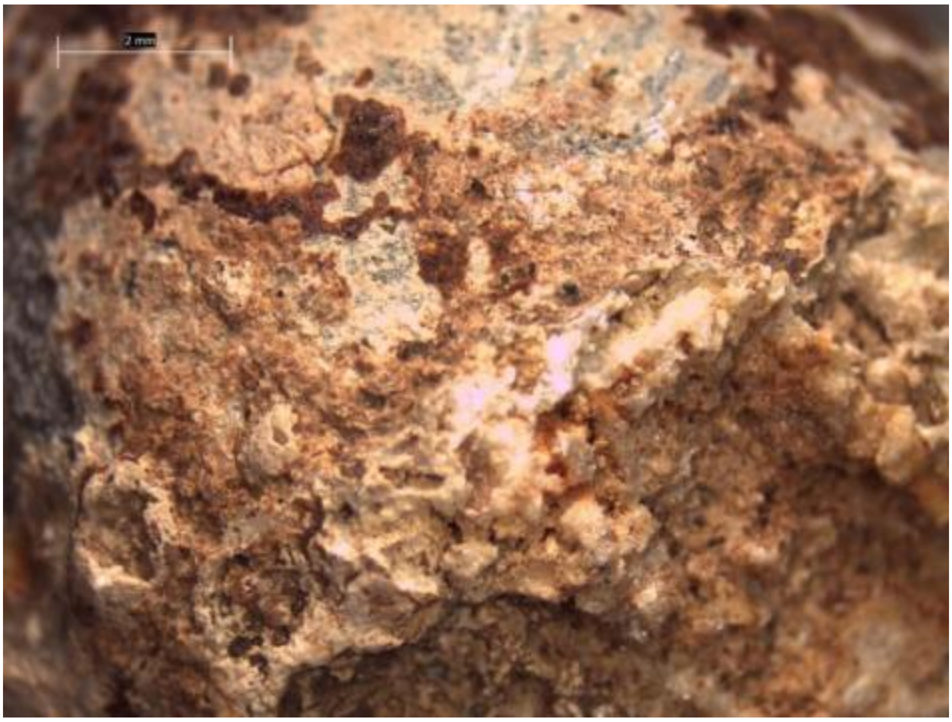


Figure 67: Magnification x20 of a bullet showing severe corrosion and surface breakdown (MOR 0084).

Over a third (34%) of the bullets were noted as having eroded or abraded surfaces with significant loss of surface patina or a very gritty eroded surface texture (figures 68 and 69). There could be many reasons why the bullets have been abraded. The initial surface patina formed on the bullets may have been quite thin and not formed a thick enough barrier to protect the bullet from ground disturbance. The most likely explanation for the bullets being abraded is their presence in the ploughsoil where the soil is predominantly sands and gravels. Sand abrasion has been a problem for engineering for decades and sands made up of large coarse particles are known to be a significant problem in the abrasion of metals (Rosenberg 1930; Finnie 1960). The annual churning of the soil through ploughing will allow bullets to brush against large abrasive sand gravel particles, potentially damaging and wearing down the relatively soft lead compounds on the surface of the bullets. There is a slight positive correlation between abrasion and the sand content of soil samples; as sand content of soil increases, generally more abraded bullets are recorded (figure 70). This suggests that on sites with clay soils, abrasion would be reduced. This is true for bullets at Edgehill which show very few signs of abrasion in clay rich soils (see chapter 6).

It may be assumed that abraded bullets would be left vulnerable to develop areas of localised corrosion if the surface patina is compromised. It is interesting to note that 60 bullets had localised corrosion and 61 bullets had evidence of abraded surfaces, but only 16 bullets had evidence for both, indicating that there is not a large correlation between abrasion and developing localised corrosion. This could be due to the limited time period the bullets have been subjected to cultivation. Abrasion is likely to have occurred since the recent conversion to arable and it may be that if ploughing continues in these fields, serious localised and intergranular corrosion could develop on bullets that have had their protective patinas weakened by prolonged abrasion in the ploughsoil. The Wareham collection has been under the plough for several decades, if not centuries, longer than the Moreton Corbet assemblage and show greater signs of abrasion and localised corrosion (see chapter 7). Abrasion is also largely to do with soil texture and is less likely to occur in clay-rich soils as clay particles are smaller, smoother and are plate-like with less severe angular structures than sand particles.

Very few bullets had cracked or powdery surfaces in the Moreton Corbet assemblage. Powder often indicates post excavation corrosion rather than corrosion in the ground, suggesting that the bullets have been stored appropriately (Schindelholz 2001; Watkinson and Neal 1987). 14 bullets showed evidence for severe cracking, which could be an indication of stress corrosion cracking caused by the breakdown of the surface patina (Edwards 1996).

Figure 68: Bullet with thin patina and loss of surface (MOR 0291).

Figure 69: Magnification x20 of a bullet surface showing abraded texture and subsequent pitting exposing underlying layers (MOR 0191).

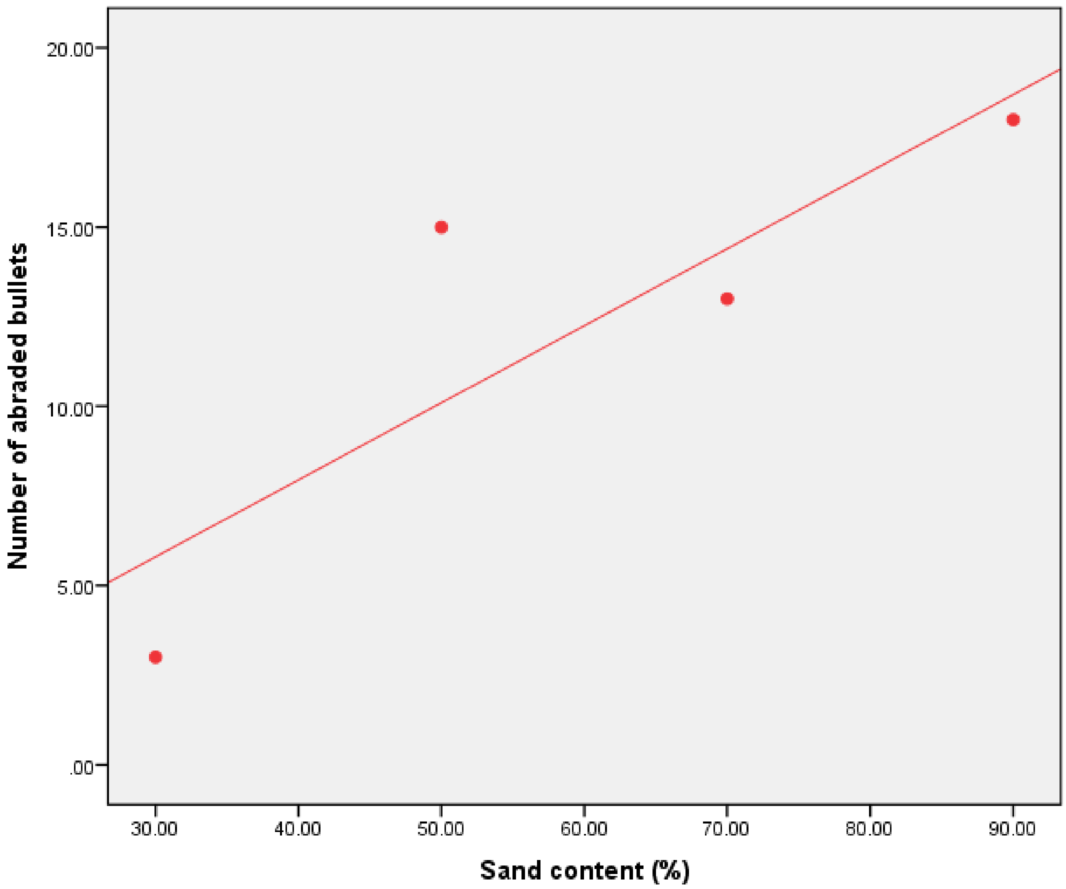


Figure 70: Number of abraded bullets compared to the sand content (%) of soil samples, indicating that as sand content increases, the number of abraded bullets increases.

During assessment it was observed that bullets which appeared to have thin patinas had often suffered abrasion damage. Research has already been carried out on a small scale to measure corrosion depth on surface patinas of bullets (Woodruff 2015, 41). In this previous study one bullet was half sectioned to analyse the depth of corrosion penetration which had reached a severe depth of 1910µm (1.91mm) (figure 71). As this involved cutting the bullet in half which is highly destructive, it was deemed inappropriate to carry out further such measurements and a less destructive method was designed.

For this study four bullets were selected to measure the patina corrosion depth, two with abraded surfaces and two without. A small area of the surface was scraped away and a digital microscope was used to measure the thickness of corrosion. The depth of corrosion was measured at five separate intervals and averaged (table 34).

The results revealed that the bullets that were abraded had a thinner patina than those which had not been severely abraded. The abraded bullets' patina averaged at

79.75±30.89µm thick whilst the non-abraded patinas averaged at 168.94±79.67µm thick. The greatest difference was between bullets MOR 0014 and MOR 0191 which differed by 167.37µm (figures 72 and 73). There was little difference however, between the abraded bullet MOR 0239 and the non-abraded bullet MOR 0250 which had a difference between them of only 11.02µm. The bullets that were not abraded also scored an overall condition of 1 for very good condition. However, there are many bullets in the collection that exhibit severe corrosion and have substantial layers of corrosion. This highlights two separate issues; erosion and abrasion of surfaces, and localised corrosion, both of which are problematic to the survival of bullets. It appears that those bullets which have suffered more abrasion have lost a percentage of their patina through erosion and their condition has suffered, whilst bullets that have not been abraded have retained their protective patina. Further analysis and experimentation would be required to define at what rate patinas are being lost through abrasion in the soil. Abrasion will be discussed further in section 8.2.

Figure 71: Half-sectioned bullet to measure depth of corrosion (MOR 0084).

Bullet	Corrosion thickness (averaged from five measurements)
MOR 0014 (not abraded), condition 1	225±44µm
MOR 0191 (abraded), condition 4	58±17µm
MOR 0239 (abraded), condition 3	102±34µm
MOR 0250 (not abraded), condition 1	113±29µm

Table 34: Corrosion thickness of four selected bullets.

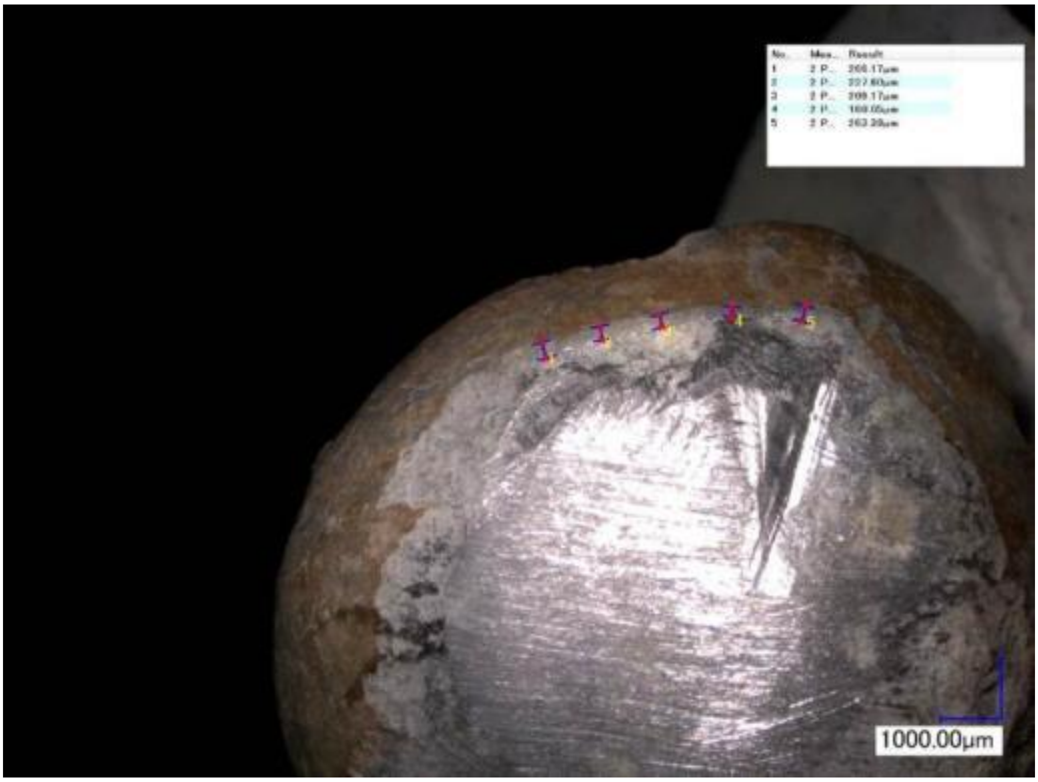


Figure 72: Scraped patina to measure corrosion thickness (MOR 0014).

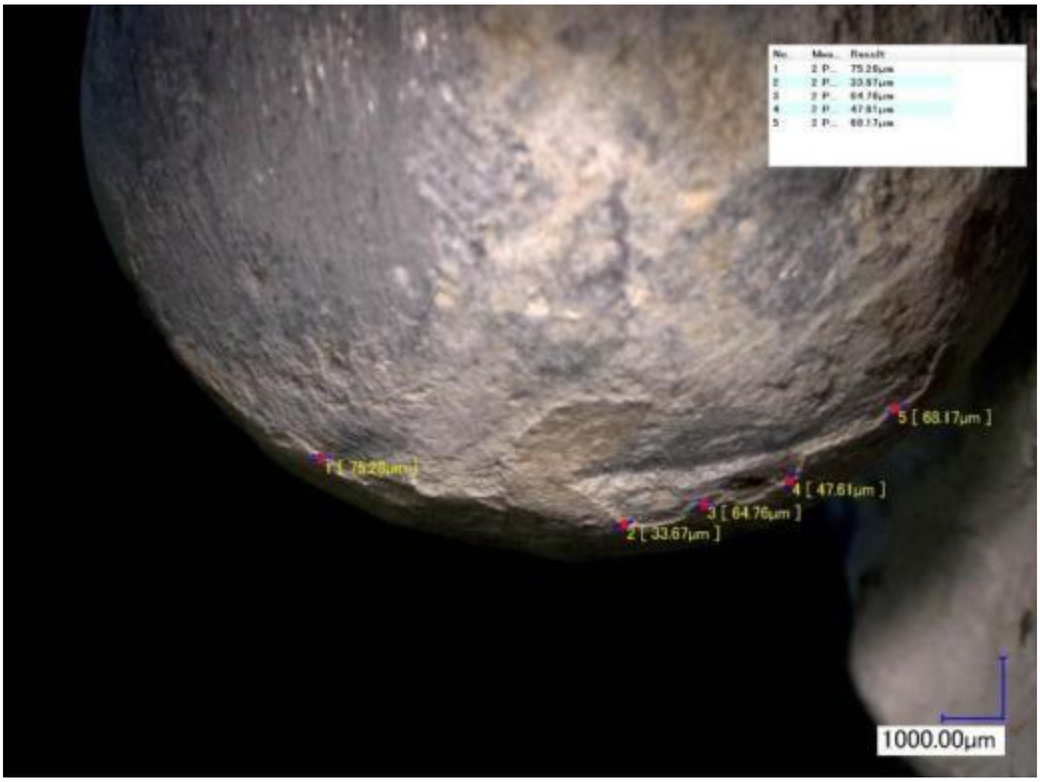


Figure 73: Scraped patina to measure corrosion thickness (MOR 0191).

5.6 Bullet composition and corrosion products

30 bullets from Moreton Corbet were analysed using XRF to examine their metallic composition, as laid out in the methodology (4.5.2). This was done to address whether variations in lead content had any effect on the overall condition of the bullets. The lead content ranged from 81.7% to 96.1%, with an average content of 92.22±3.44%. All bullets also contained an amount of metallic tin. Tin content ranged from 0.54% to 15%, with an average content of 1.95±3.17%. When the composition results are compared to the condition score of the bullets, there does not appear to be a clear relationship between lead or tin content and overall condition, as both very good and poorly preserved bullets contain high levels of tin. Similarly, bullets with high levels of lead still score 4 for poor condition indicating that as lead content increases, condition does not automatically improve.

Eight bullets were further selected to examine the corrosion products formed on the bullets, through X-ray Diffraction. Most exhibited standard lead compounds on their surface (figures 74-90), formed predominantly of cerussite, the most common lead compound. Two bullets had formed tin compounds which each contained 11.4% and 15% tin in their cores. The condition of the bullets from Moreton Corbet varied, though there does not appear to be a pattern of formation of corrosion patterns with condition. It is interesting that the two bullets which have only formed cerussite with no other products are both in poor condition, scoring a 3 or 4. These two bullets exhibit patina breakdown and pitting, indicating that cerussite has not formed a fully protective surface patina, failing to protect the underlying metal from attack. Other bullets with several compounds including cerussite, hydrocerussite and chloropyromorphite have preserved well with stable patinas.

The two bullets which contain tin and have formed tin compounds are at either extremes of preservation. Bullet MOR 0014 has formed cerusssite, hydrocerussite, and massicot, alongside herzenbergite and it is in a very good stable state of preservation. Bullet MOR 0264 has formed very similar compounds as well as cassiterite, but is in a poor state of condition and the patina has been abraded and lost in parts. This suggests that simply looking at the compounds formed on the bullets will not indicate how well they will preserve. The formation of cerussite alone does not necessarily protect the underlying metal from further decay. The formation of corrosion products is a complex process and in future it may be beneficial to carry out more in depth analysis to establish the order in which compounds are formed to assess whether particular layers provide better protection for the underlying metal.

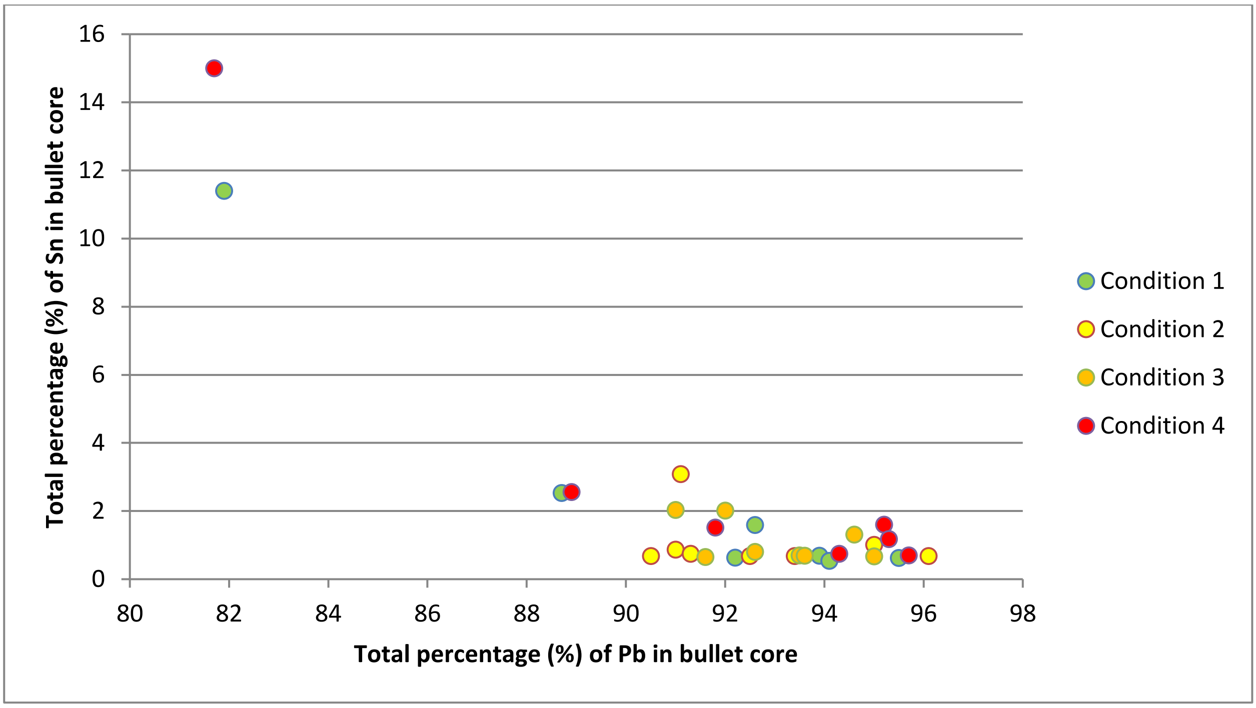


Figure 74: Lead and tin content of bullets from Moreton Corbet and corresponding overall condition scores. It is evident that bullets with high levels of lead or high levels of tin can still score 1 or 4 suggesting composition has had little effect on preservation.

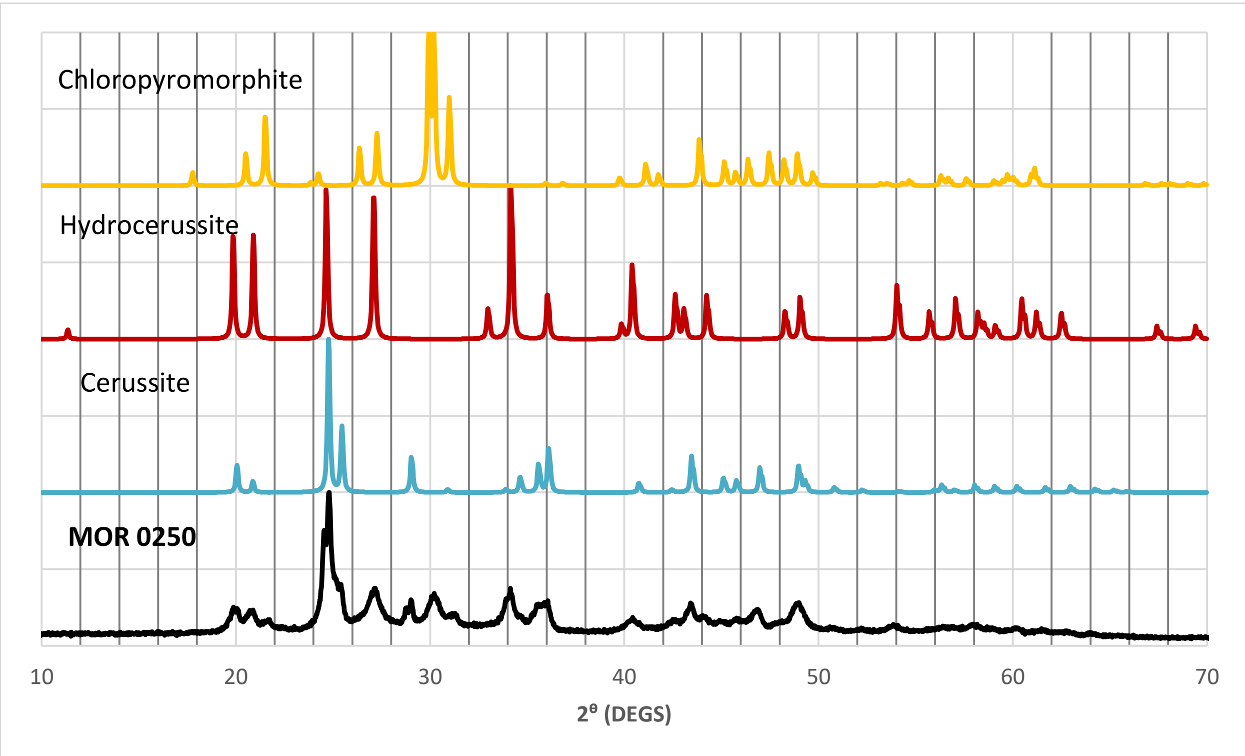


Figure 75: XRD spectra for bullet MOR 0250. The main compounds present are cerussite, hydrocerussite, with traces of chloropyromorphite. This bullet contains 88.7% lead.

Figure 76: Bullet MOR 0250 with stable patina and good surface detail. Condition score 1, very good.

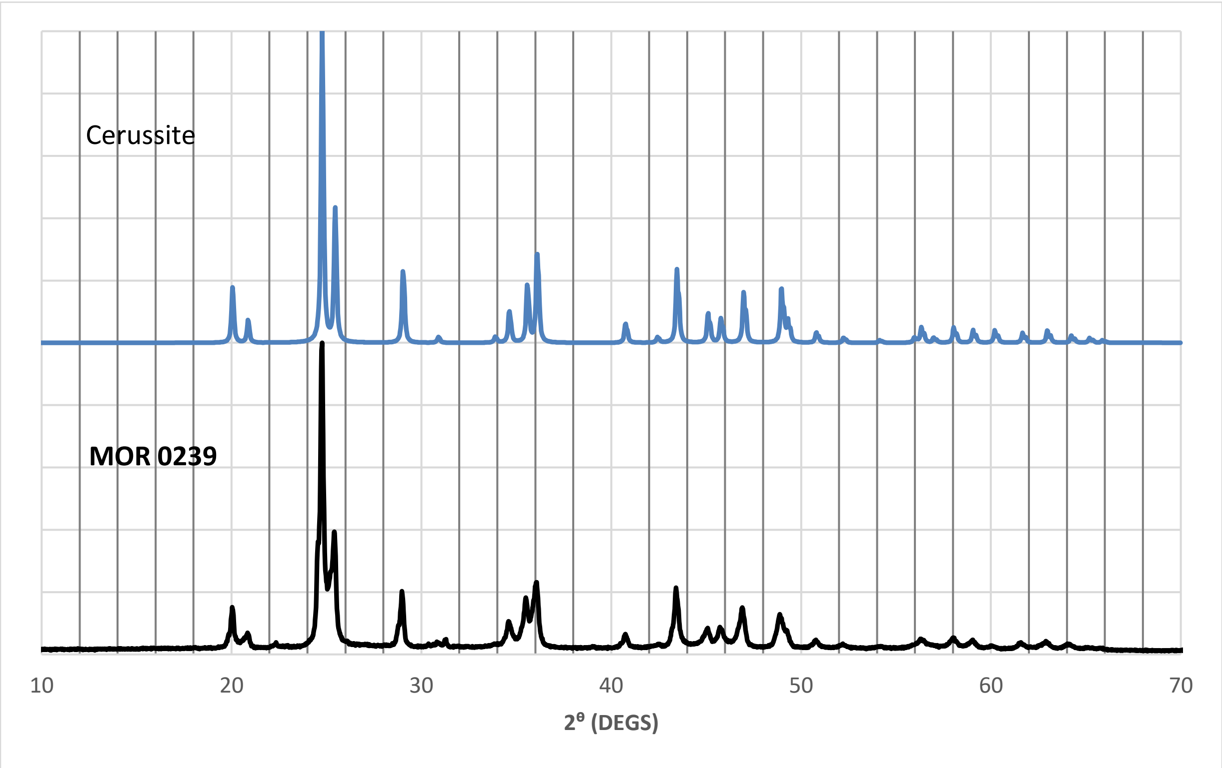


Figure 77: XRD spectra for bullet MOR 0239. The only compound present is cerussite. This bullet contains 92% lead.

Figure 78: Bullet MOR 0239 with pitting and deterioration of surface patina. Condition 3, fair.

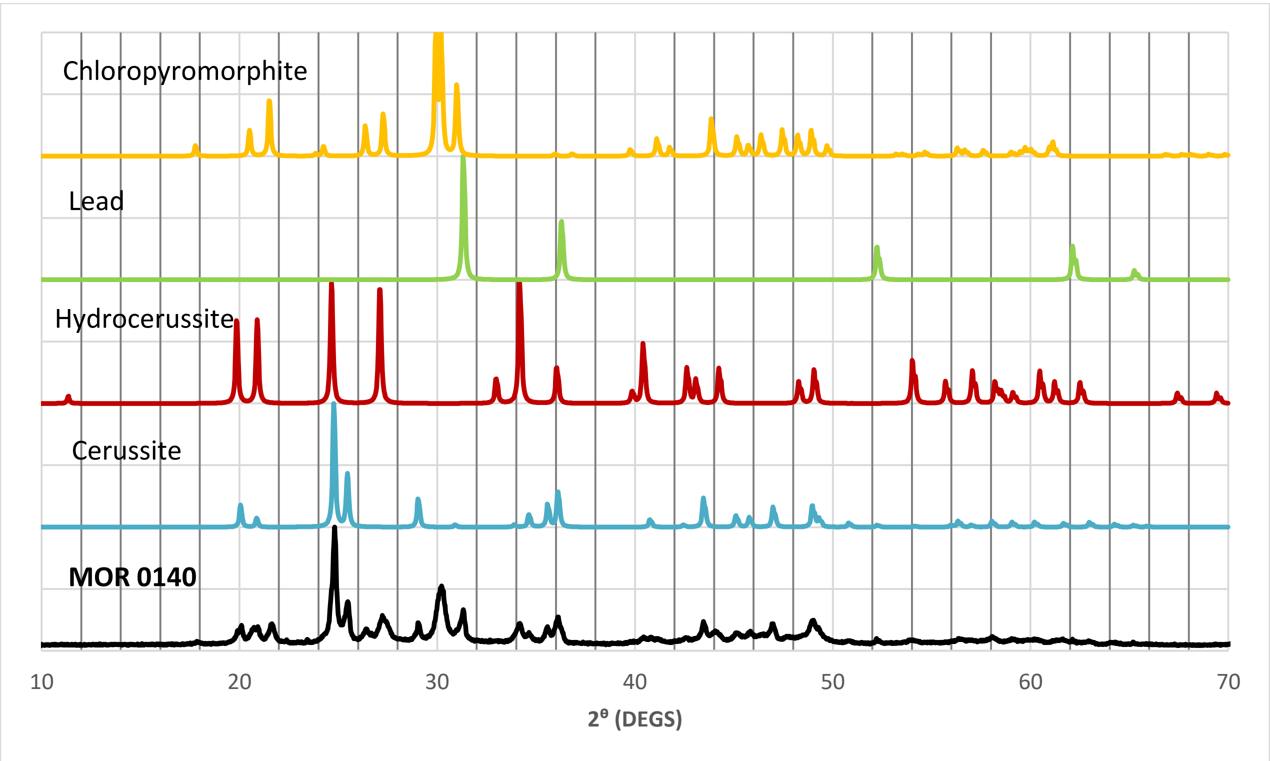


Figure 79: XRD spectra for bullet MOR 0140. The main compounds present are cerussite, chloropyromorphite, hydrocerussite, and metallic lead. This bullet contains 92.2% lead.

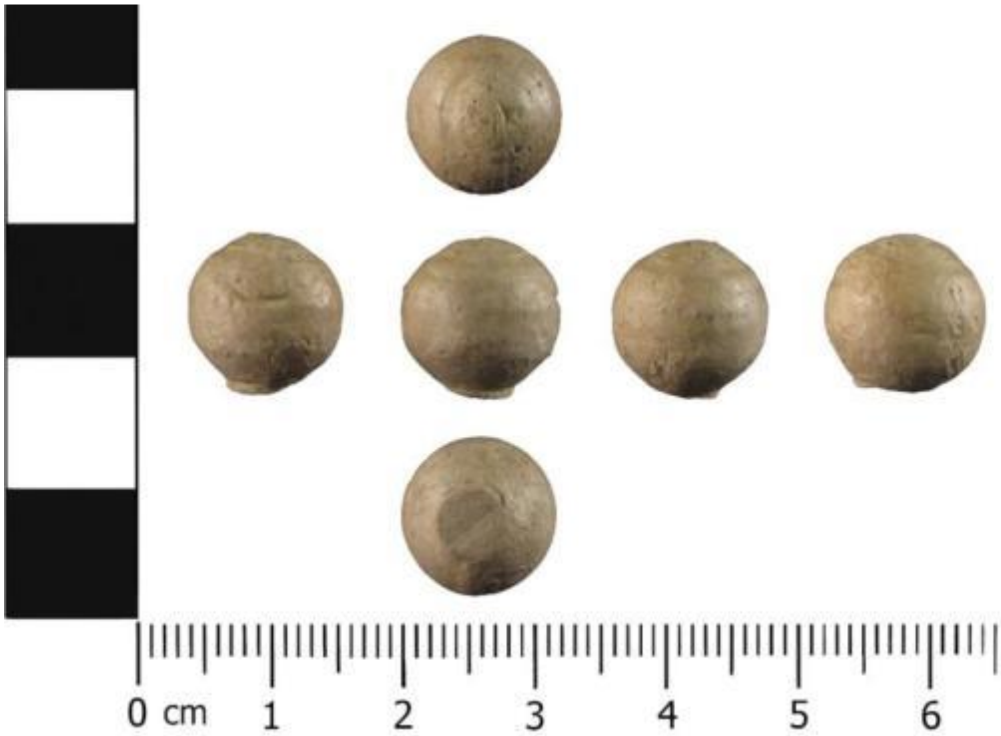


Figure 80: Bullet MOR 0140 with smooth patina and details. Condition score 1, very good.

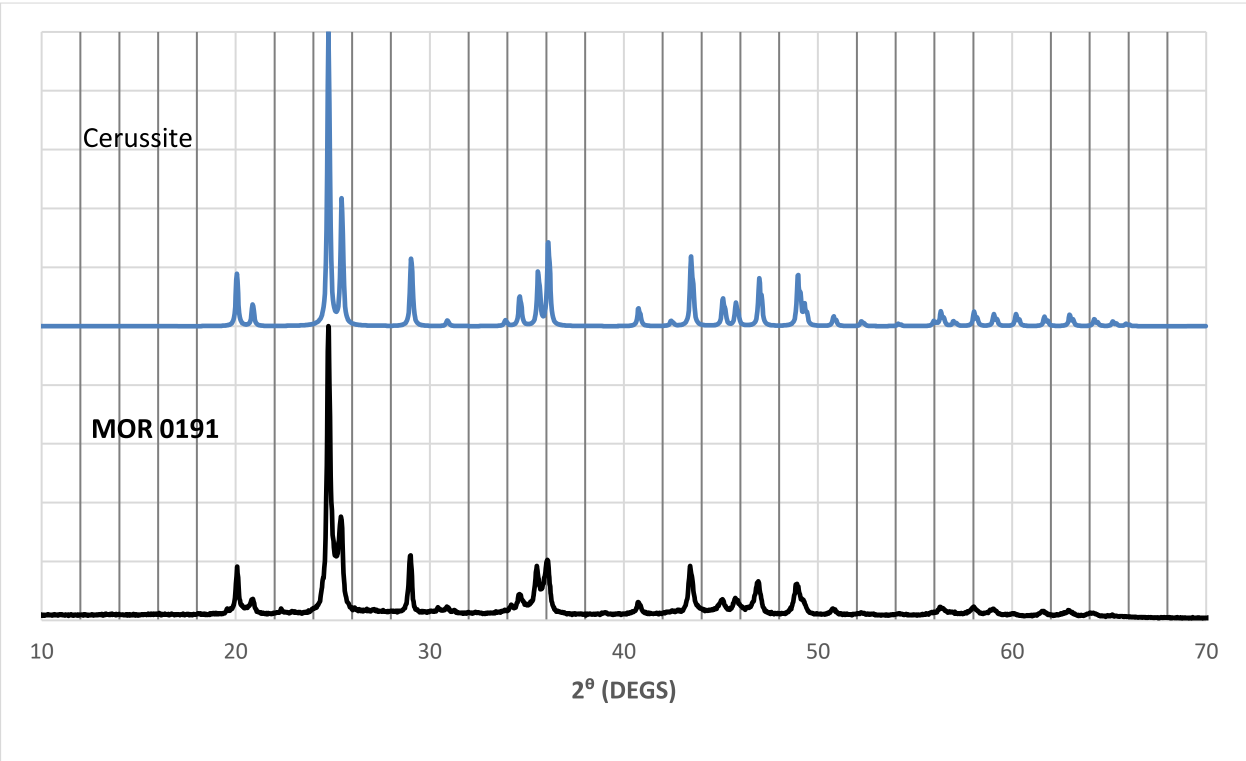


Figure 81: XRD spectra for bullet MOR 0191. The only compound present is cerussite. This bullet contains 91.8% lead.

Figure 82: Bullet MOR 0191 with severe loss of surface and pitting. Condition 4, poor.

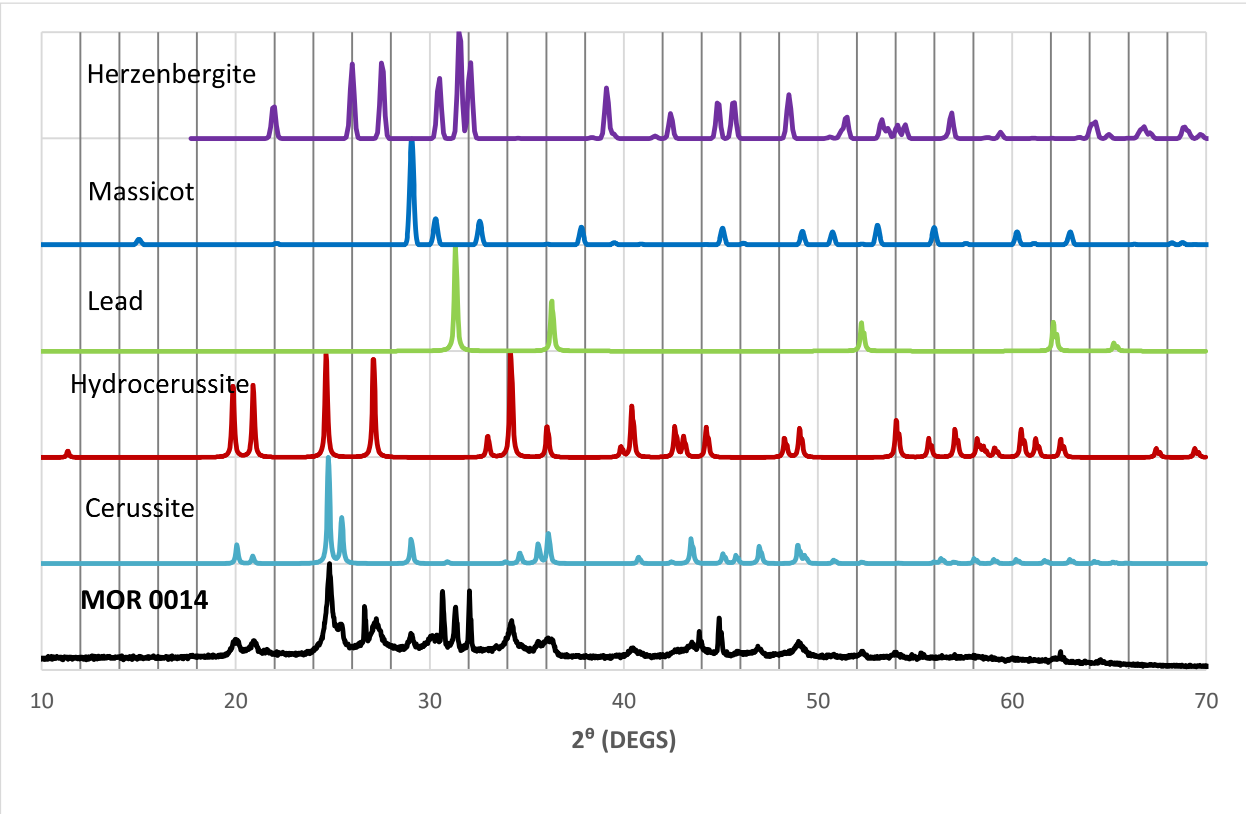


Figure 83: XRD spectra for bullet MOR 0014. The main compounds present are cerussite, herzenbergite, hydrocerussite, with traces of metallic lead and massicot. This bullet contains 81.9% lead and 11.4% tin.

Figure 84: Bullet MOR 0014 with smooth stable patina and clear details. Condition 1, very good.

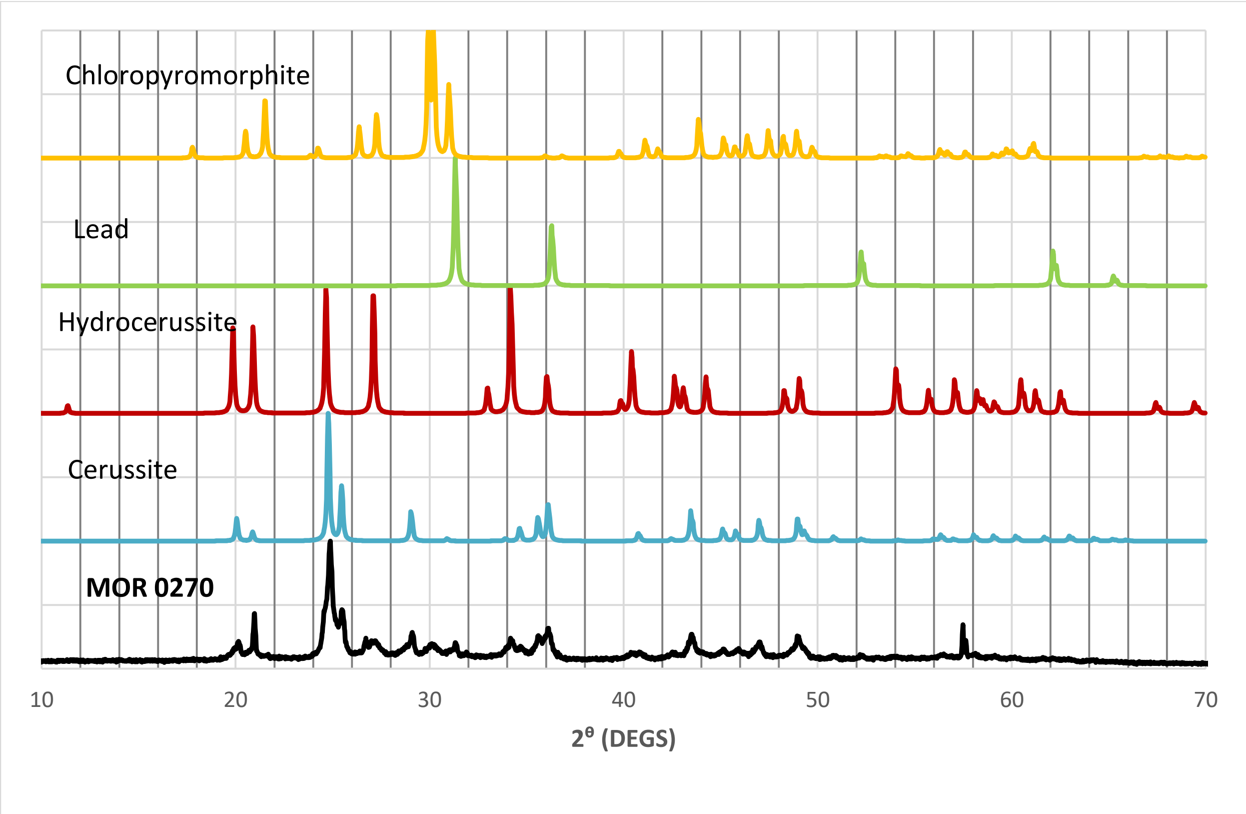


Figure 85: XRD spectra for bullet MOR 0270. The main compounds present are cerussite, and traces of metallic lead, hydrocerussite and chloropyromorphite. This bullet contains 96.1% lead.

Figure 86: Bullet MOR 0270 exhibiting some loss of surface. Condition 2, good.

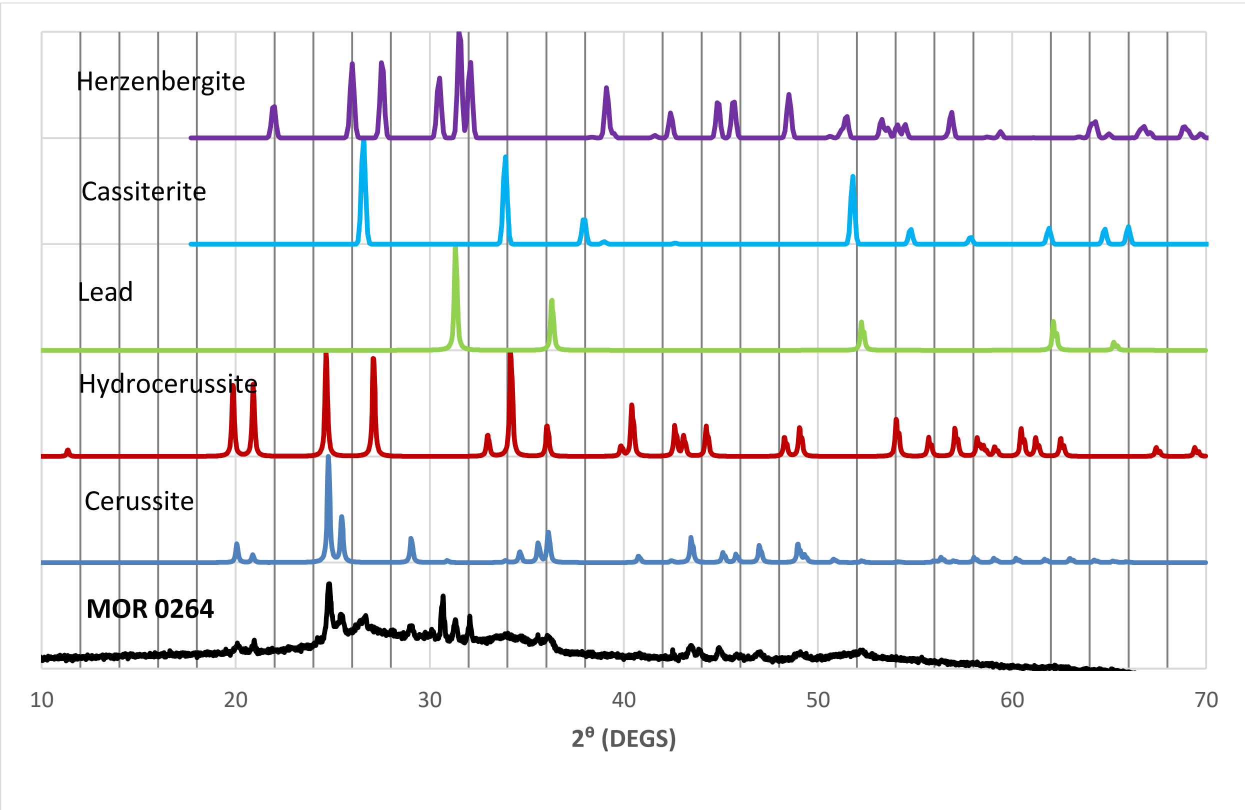


Figure 87: XRD spectra for bullet MOR 0264. The main compounds present are cerussite, herzenbergite, cassiterite, with traces of metallic lead and hydrocerussite. This bullet contains 81.7% lead and 15% tin.

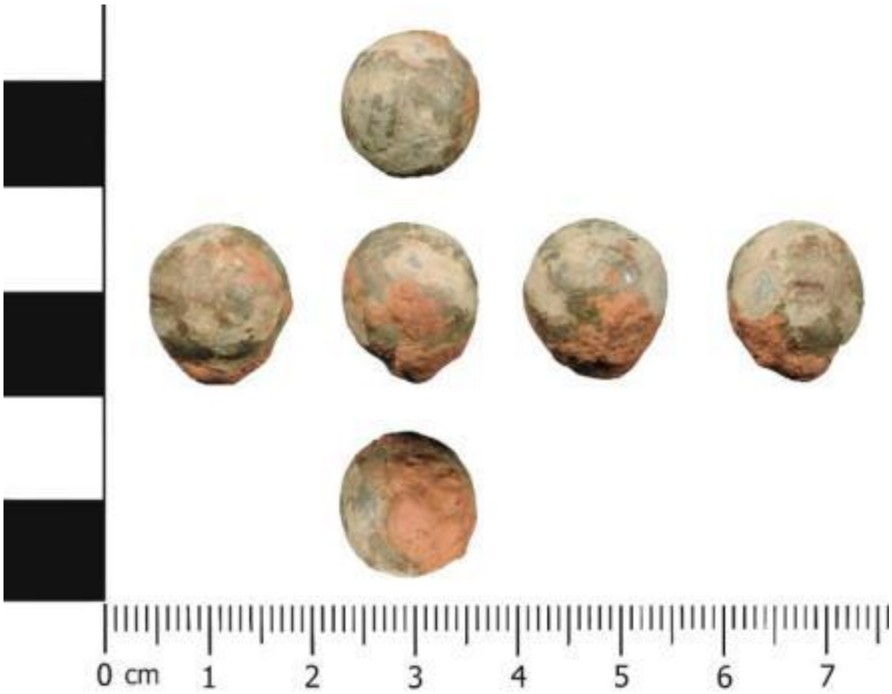


Figure 88: Bullet MOR 0264 with abraded surface and loss of patina (with adhered unidentified ferrous compound). Condition 4, poor.

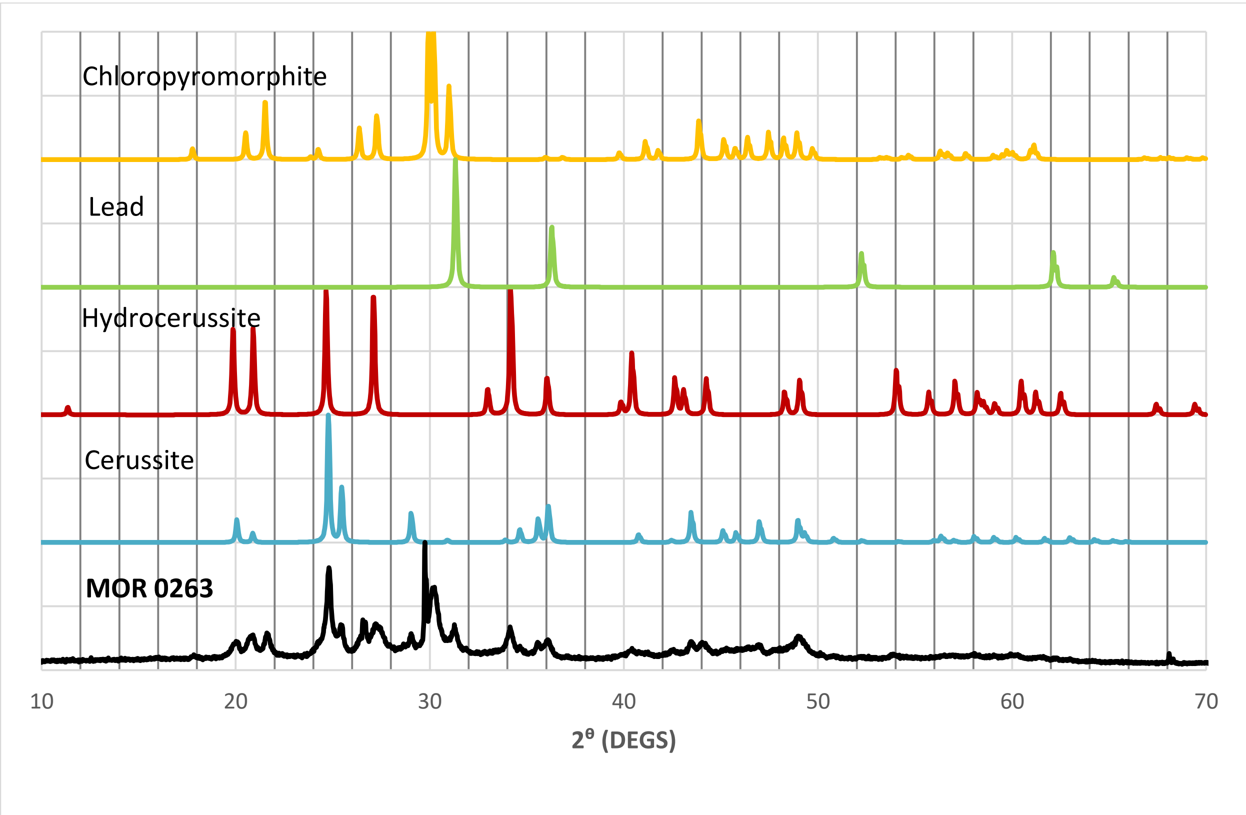


Figure 89: XRD spectra for bullet MOR 0263. The main compounds present are cerussite, chloropyromorphite, hydrocerussite, and metallic lead. This bullet contains 88.9% lead.

Figure 90: Bullet MOR 0263 with rough surface, pitting and loss of patina. Condition 4, poor.

5.7 Soil data and bullet condition analysis

In order to compare the condition of bullets with their burial conditions, tests were run on soil samples gathered from the site. Test pits were sampled from three distinct soil contexts in order to characterise the ploughsoil as a separate context from the underlying deposits (table 35). Each test pit and corresponding contexts were tested for their pH, conductivity, water content, organic matter content, colour, consistency and texture. Selective samples were also tested for chloride and nitrate levels. A total of 79 soils samples were processed from 30 test pits.

In order to address whether any parameters have a significant impact on the condition of the bullets, statistical analysis was carried out for each soil parameter against the condition of lead bullets. Spearman's rank statistical analysis was applied as it involved identifying correlations between two variables; the condition of the bullets and the individual soil parameter (see appendix V for a background on the statistical method).

Soil context	Soil depth range	Soil depth average
Topsoil	0.20-0.37m	0.28m
Subsoil	0.30-0.60m	0.44m
Lower subsoil	0.45-0.90m	0.70m

Table 35: Recorded soil contexts and corresponding depths.

5.7.1 pH results

pH levels across the site varied from 5.49 to 7.44 $CaCl_2$ (5.68-8.05 H_2O). $CaCl_2$ will be the primary results discussed as it is deemed more accurate than water measurements (discussed in section 4.5.1.3).

As a site trend, pH increases with soil depth, and on average topsoils are more acidic than subsoils. Topsoil pH ranges from 5.49 to 7.29, with an average of 6.05±0.43. Subsoils range from 5.55 to 7.44 with an average of 6.39±0.43, and lower subsoils range from 5.67 to 7.23, with an average of 6.56±0.47 (figure 91). Though there is great variation in topsoil pH across the site, 50% of the data lies between a pH of 5.66 and 6.29 indicating that the soil is mainly slightly acidic.

In order to understand how pH varies across the site, the pH of the topsoil was mapped. Certain areas appeared slightly more acidic than others. A 'neutral' soil has a pH range between 6.5 and 7 (Rowell 1994, 153). However, because all but four topsoil samples from the site are below pH 6.5, topsoil was deemed 'acidic' below pH 6 to better identify acidic areas across the site. pH was mapped using ranges of pH (figure 92). The map reveals that most of the topsoil has a pH of 5.5 to 6.5, with only four topsoil samples reading over pH 6.5. All four of these samples lie to the eastern side of fields B and C which corresponds with down slope areas on the site of 67m AOD or lower. Higher ground to the west of the site is predominantly acidic in Field C and the former track way in Field B.

It is evident that the areas upslope to the west in the area of the former gardens and above the garden terrace boundary, the soil is predominantly acidic. This may be in part due to the western end of Field C being used for pig farming in the late 20th and 21st centuries (see section 5.4.3). Pig slurry and urine can lower soil pH whilst increasing levels of ammonia and nitrogen. However, it has been shown that pig slurry can also raise soil pH, so this may not be the reason for increased acidity levels (Zhang 1998; de Oliveira, Pinheiro, and da Veiga 2014). In the subsoils, it becomes clear that the eastern edge of the site is predominantly neutral to slightly alkaline past depths of 0.45m, but areas in Field C upslope around the former gardens remain below pH 6.5, with the former grassed track way in Field B also remaining lower than pH 6.0, at pH levels 5.82 and 5.67.

In terms of soil aggressiveness, the pH range is just inside a 'safe' range for the survival of lead. Anything below pH 5.5 would start to seriously impact on the dissolution of lead (see section 2.1.3) (Costa and Urban 2005, 50; Goodwin 2006, 771). 50% of the topsoil samples do however, fall below pH 6, all being between 5.49 and 5.95 which is on the verge of being aggressive acidity levels towards lead. If these were found to fluctuate and increase in acidity throughout the year due to land use, the addition of fertilisers and manure, reduced levels in calcium, or acid rain which tends to increase acidity, then this may account for bullets being in worse condition than others. This would require ongoing long term soil sampling procedures to be carried out on the site throughout the year.

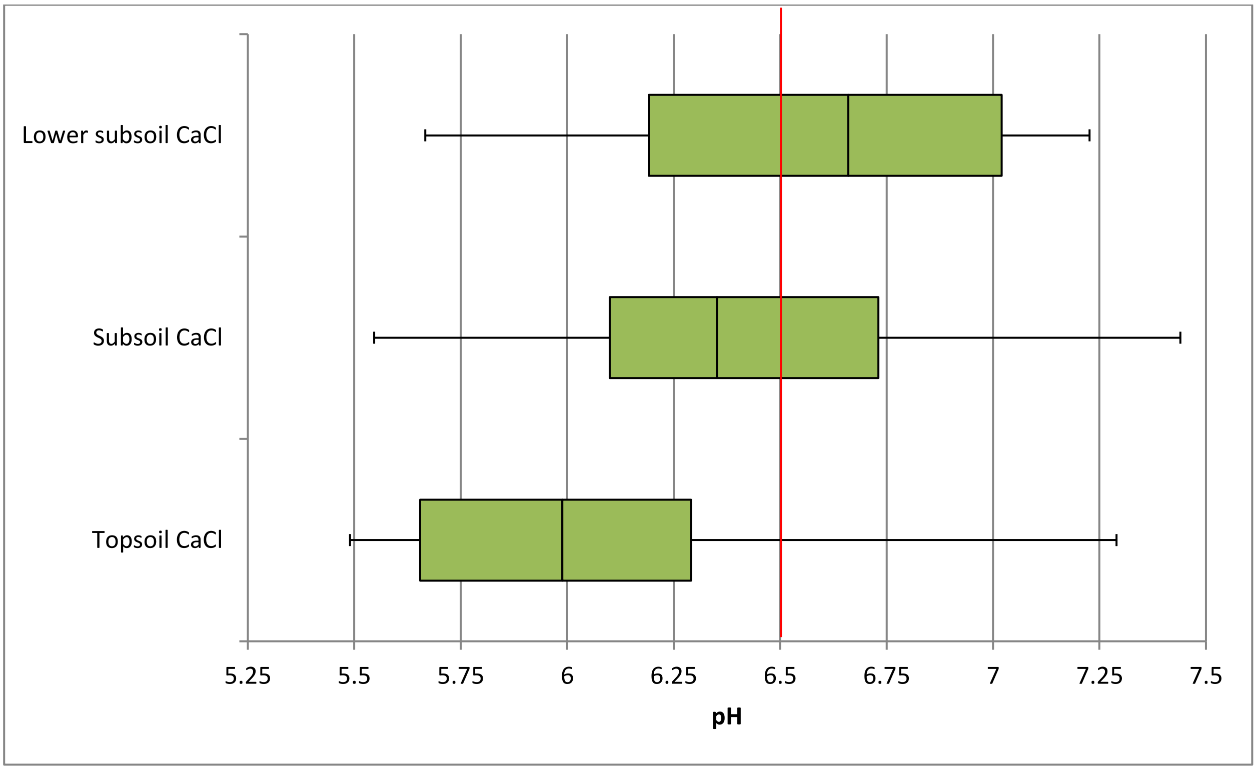


Figure 91: Box plots showing pH range of all soils from each context with pH gradually increasing with soil depth. The ends of the boxes signify the lower and upper quartiles of the data, with the green area representing 50% of the data. The central line marks the median and the whiskers at both ends represent the lowest and highest pH observations. The red line indicates a neutral soil pH.

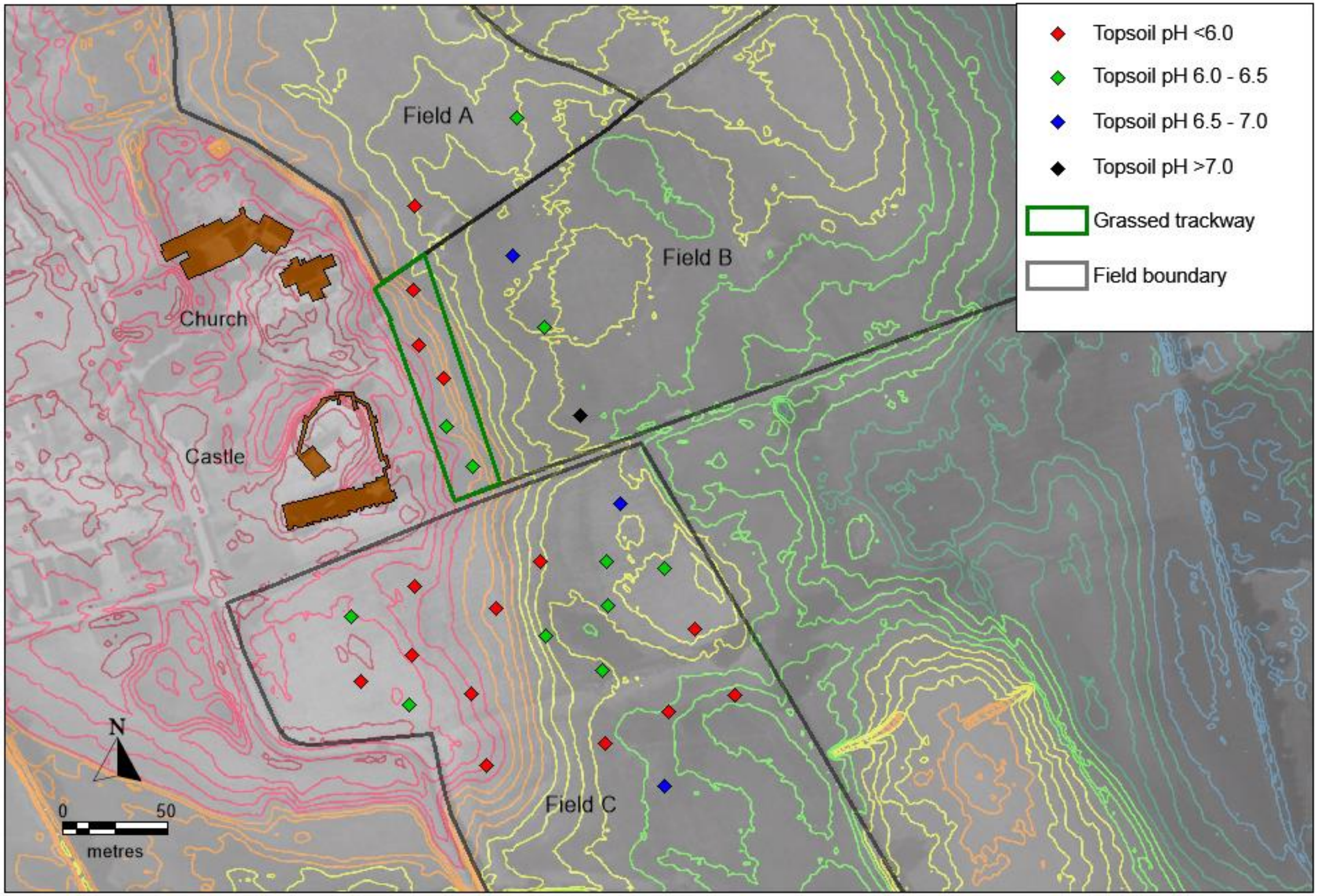


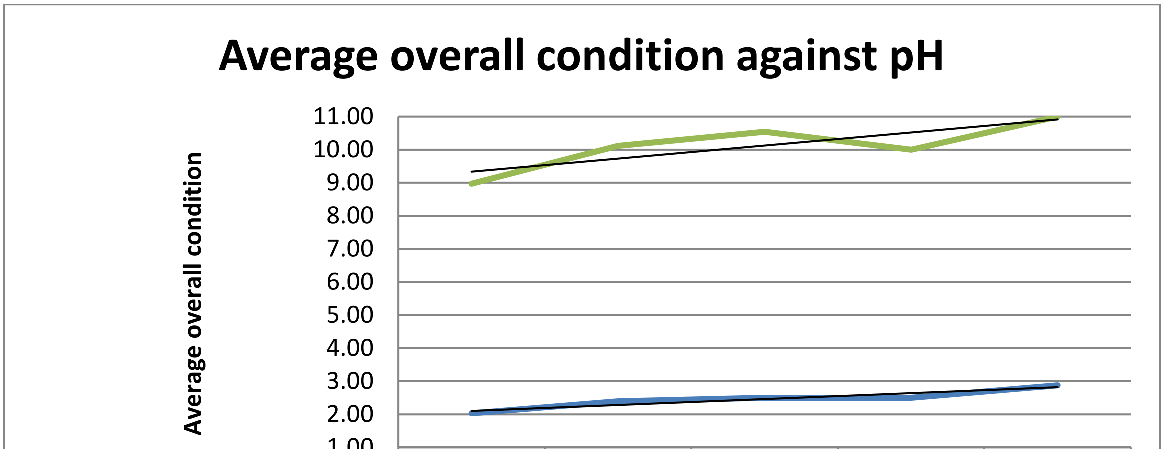
Figure 92: Topsoil pH levels at Moreton Corbet. Areas upslope to the west are predominantly acidic, whilst areas down slope to the east are predominantly neutral to alkaline. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

5.7.1.1 pH levels against bullet condition

When the average condition scores for bullets from each pH range is plotted (figure 93) it is apparent that there is a very slight tendency for condition score to increase as pH increases. This is against the prediction that as pH enters a neutral to alkaline range, condition would be expected to improve and therefore condition score to decline. In theory, the ideal pH range for metals is 5.5 to 8.5. However, these results suggest that bullets are preserved well in areas where pH is below 6.

When each data point is plotted against pH (figure 94), this very slight positive correlation is apparent between the two variables. However, the relationship is weak. The correlation coefficient value (r) of 0.1 indicates a weak relationship and is close to 0 (table 36). This coefficient value is not statistically significant which reveals that there is no significant correlation between condition and pH on the site. As discussed above, the pH range at the site is not particularly dangerous to the survival of lead as no levels drop below pH 5, so this lack of correlation is not surprising.

The lack of correlation between bullet condition and pH on the site suggests that slight variation in acidic levels do not have a significant effect on lead preservation on the site. As discussed above, acidity dominates upslope areas in the former terraced garden areas on the site which contain the best preserved bullets on the site. Bullets residing down slope in neutral to alkaline soils, which in theory should promote their preservation, are less well preserved, suggesting that another parameter other than pH is affecting their deterioration.



	5.50-5.80	5.80-6.10	6.10-6.40	6.40-6.70	6.70-7.30
Average overall condition	2.03	2.40	2.50	2.50	2.875
Standard deviation	0.67	0.81	0.76	0.80	0.64
Average total condition	8.97	10.11	10.54	10.00	11.00
Standard deviation	1.82	2.53	2.38	2.83	2.39

pH range

Figure 93: Average condition score for bullets from Moreton Corbet plotted against pH range, indicating a slight trend for condition score to increase as pH increases.

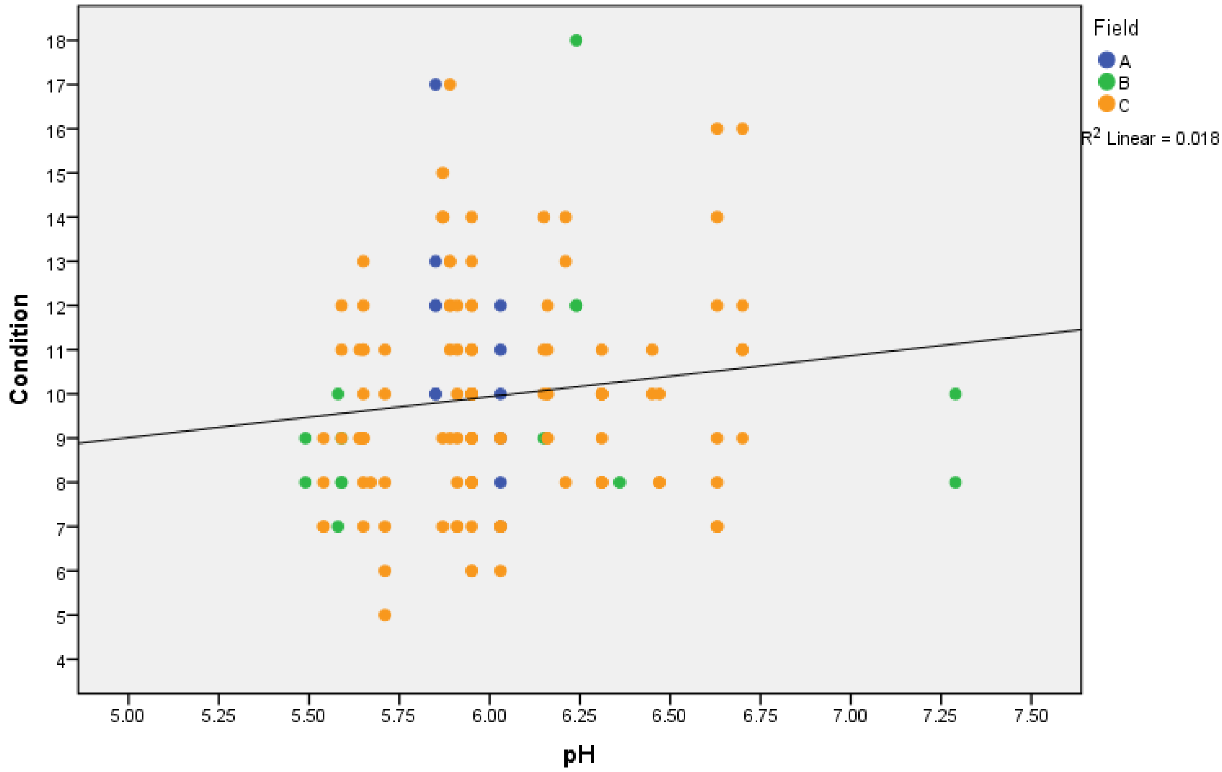


Figure 94: Scatter plot showing pH of soil against the condition of bullets, showing no clear trend.

			pH	Condition
Spearman's rho	pH	Correlation Coefficient	1.000	.100
		Sig. (2-tailed)	.	.233
		N	143	143
	Condition	Correlation Coefficient	.100	1.000
		Sig. (2-tailed)	.233	.
		N	143	143

Table 36: Spearman's rank correlation coefficient of 0.1 for the relationship between pH and bullet condition. The low value indicates the correlation is not significant.

5.7.2 Conductivity results

Conductivity levels across the site ranged from 13.43 to 425.33µS/cm. Levels were highest in the topsoil, which range from 60.20 to 425.33µS/cm, with average levels of 154.60±82.77µS/cm (figure 95). Subsoil averages at 44.63±24.64µS/cm and lower subsoil averages at 38.65±14.76 µS/cm. Soil depth makes a significant difference to conductivity levels, with greater range of levels in topsoils, whilst lower deposits are consistently low (figure 96).

In terms of soil aggressiveness, the higher the conductivity, the higher the soil aggressiveness potential. Studies have shown that levels above 200µS/cm could lead to an aggressive soil environment for metals (Corcoran *et al.* 1977; Wilson 2004). 23% of the topsoil samples were recorded higher than this and could potentially affect the deterioration of bullets. The conductivity of the topsoil across the site was mapped using ranges to highlight contrasts in levels (figure 97). The lowest levels below 100µS/cm are quite well distributed across the three fields. Highest levels above 200µS/cm all appear in Field C, except two readings. Field B has fairly low levels of conductivity, apart from two samples which are recorded as the highest levels on the entire site, both above 300µS/cm which are in an east to west alignment with each other. The rest of Field B is below 200µS/cm.

There are no clear patterns in conductivity across the site in general. Average topsoil levels of 154.60±82.77µS/cm are not particularly high, though five topsoil samples are recorded above 200µS/cm which could be deemed as aggressive levels. There is a slight tendency for conductivity to increase down slope; on average conductivity measured 133.37±65.31 µS/cm at 67m AOD and above, whilst they increased to an average of 180.92±87.58 µS/cm down slope at levels 67m AOD and below. This is likely to be related to higher water contents down slope (see section 5.7.3).

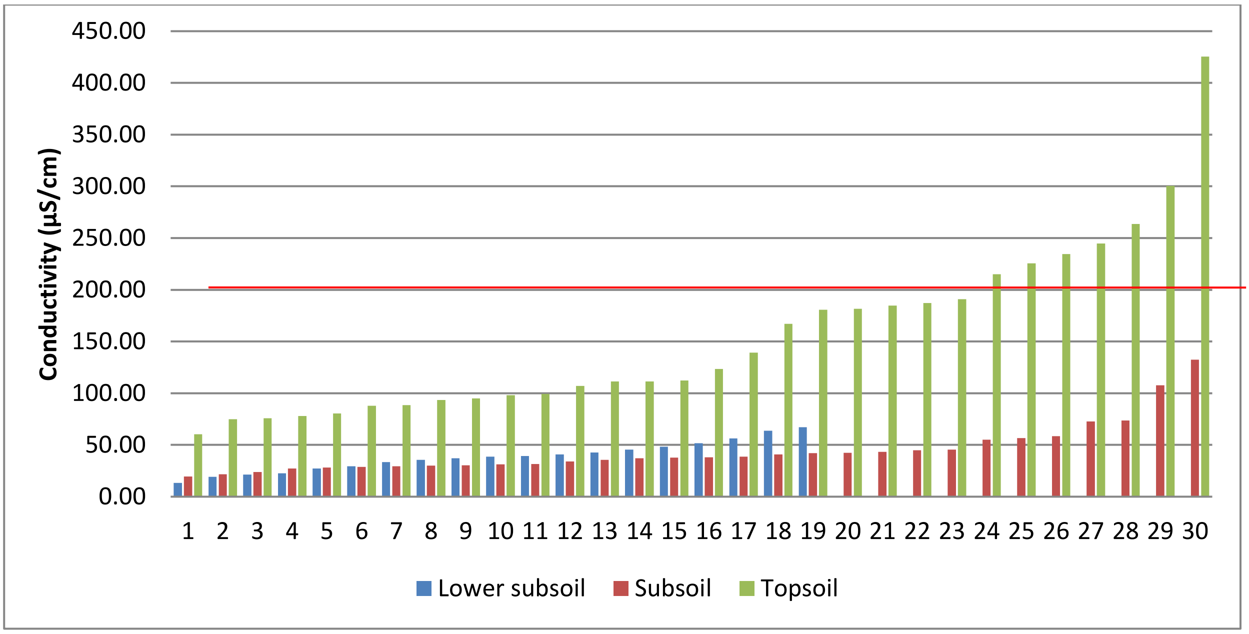


Figure 95: Conductivity levels of numbered soil samples from Moreton Corbet. Above the red line represents potentially aggressive soil conditions at 200µS/cm and above.

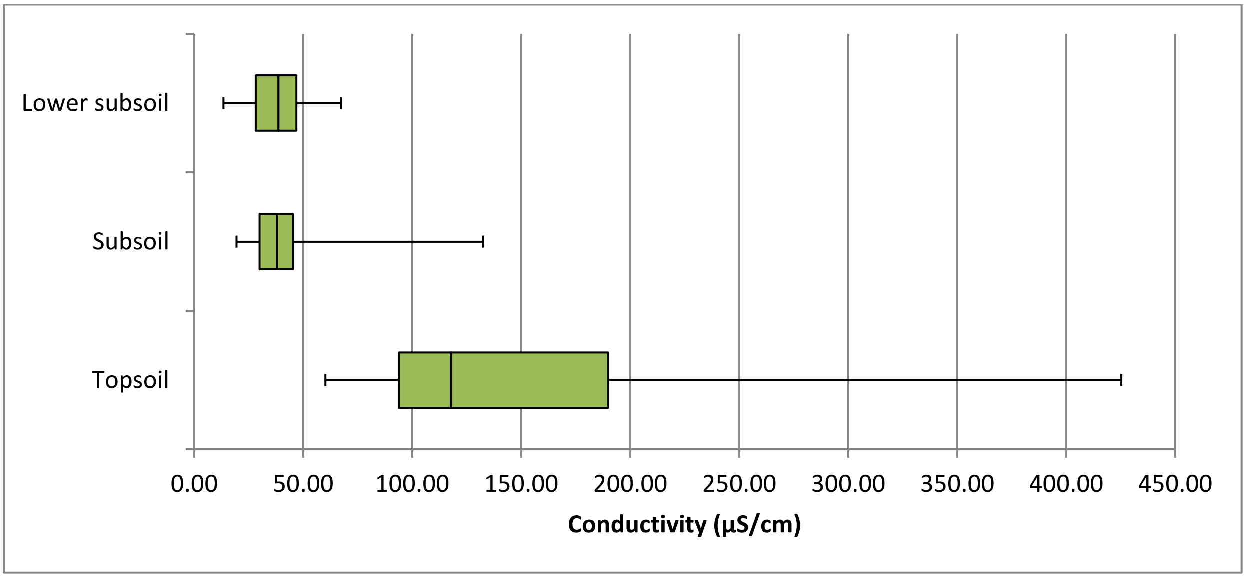


Figure 96: Box plots showing the range of conductivity in each soil level. The range is much greater in the topsoil than subsoils.

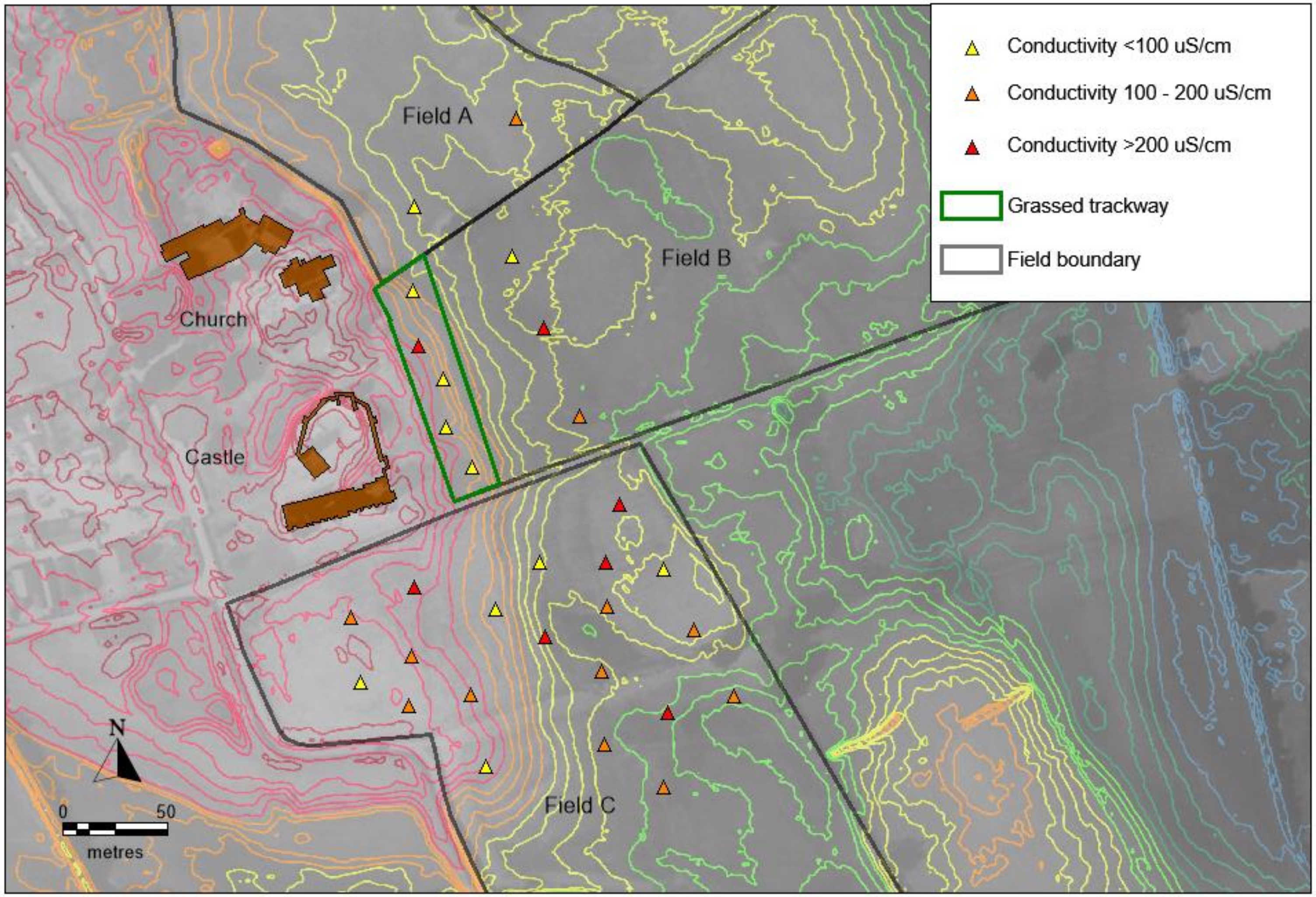


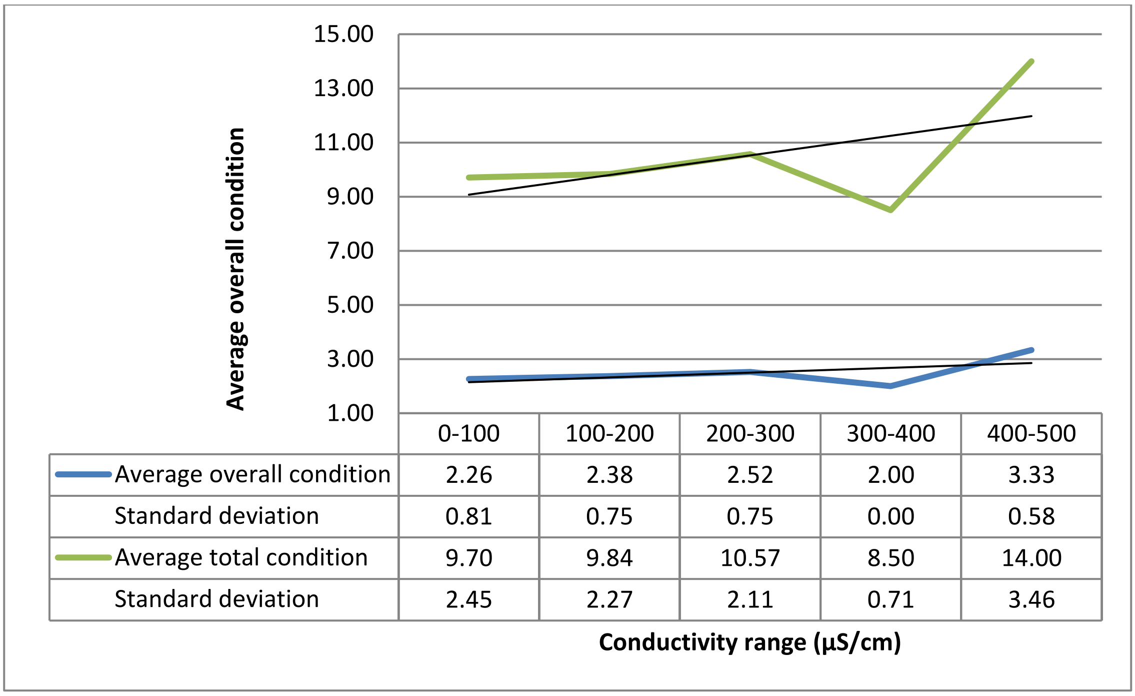
Figure 97: Distribution of conductivity levels in topsoil samples across the site, highlighting areas of low and high conductivity. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

5.7.2.1 Conductivity levels against bullet condition

When the average condition of bullets is plotted against conductivity ranges, there is a slight tendency for condition score to increase as conductivity increases, though this trend is not consistent (figure 98). Condition is fair until conductivity levels reach over 400µS/cm, where the condition deteriorated, suggesting conductivity levels need to be at approximately 400µS/cm to cause noticeable damage.

When each data point is plotted against the conductivity, there is a slight positive correlation where condition score increases with increasing conductivity, which is supported in theory that as conductivity increases, so should the rate of corrosion (Wilson 2004). However, this data is skewed by two outlying high conductivity readings from Field B, one of which is in arable which scores high and the other pasture which scores relatively low (figure 99).

There is only a very slight positive correlation between the two variables and the trend is not strong. This is supported by the correlation coefficient result of 0.131 (table 37) which is not statistically significant, meaning no statistically significant relationship between condition and conductivity levels at the site.



	0-100	100-200	200-300	300-400	400-500
Average overall condition	2.26	2.38	2.52	2.00	3.33
Standard deviation	0.81	0.75	0.75	0.00	0.58
Average total condition	9.70	9.84	10.57	8.50	14.00
Standard deviation	2.45	2.27	2.11	0.71	3.46

Figure 98: Average condition score for bullets from Moreton Corbet plotted against conductivity, indicating a slight trend for condition score to increase as conductivity increases.

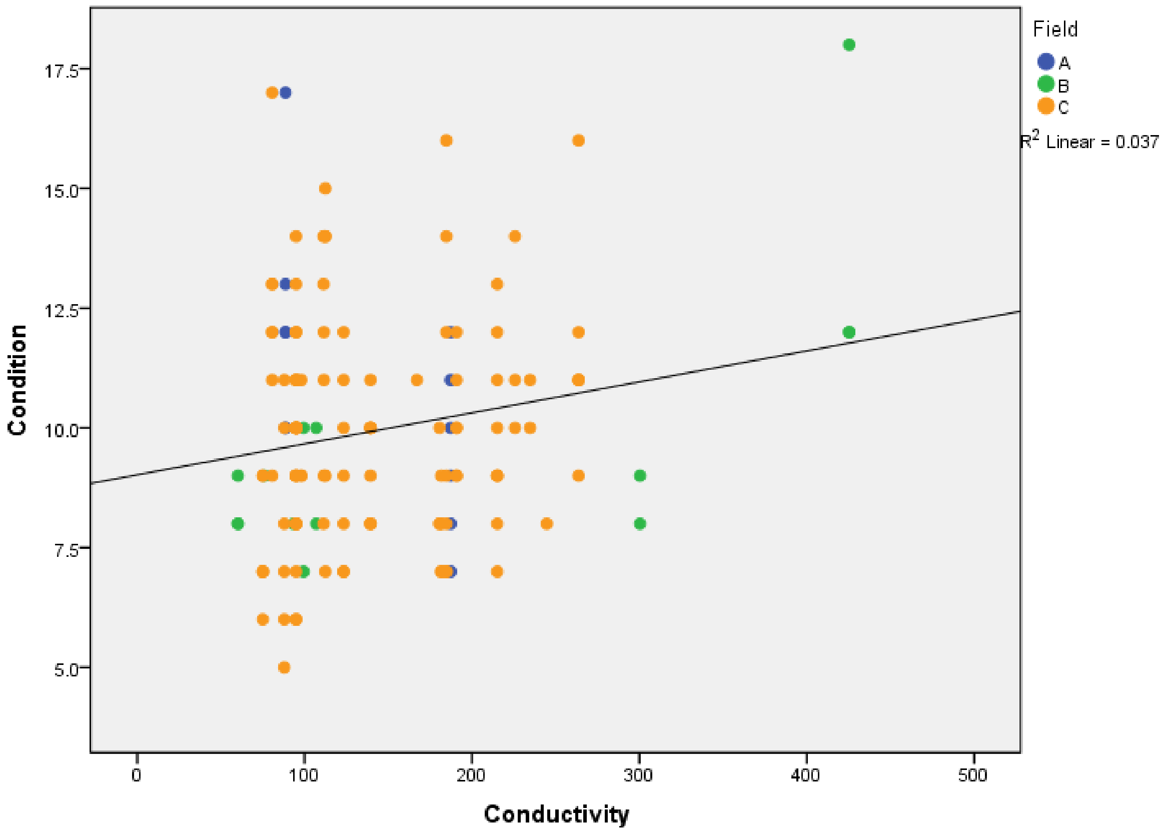


Figure 99: Scatter plot showing conductivity of soil (μS/cm) against the condition of bullets, showing no clear trend.

			Condition	Conductivity
Spearman's rho	Condition	Correlation Coefficient	1.000	.131
		Sig. (2-tailed)	.	.120
		N	143	143
	Conductivity	Correlation Coefficient	.131	1.000
		Sig. (2-tailed)	.120	.
		N	143	143

Table 37: Spearman's rank correlation coefficient of 0.131 for the relationship between conductivity and bullet condition. The low value indicates the correlation is not significant.

5.7.3 Water content results

Water content of soils across the site ranged from 4.55% to 24.63%. The highest individual measurement was recorded in the subsoil, but levels overall were higher in topsoils, ranging from 10.37% to 23.80% with an average of 15.90±0.03%. Subsoil ranged from 6.54% to 24.63% with an average of 12.91±0.04%, and lower subsoils ranged from 4.55% to 18.28% with an average of 10.65±0.03%. The difference in water contents per soil layer can be seen in figure 100. Average water content gradually decreased with soil depth, with consistently higher levels in the topsoil. Section 5.7.5 also reveals that there is a correlation with increasing water content as clay content of the soil increases due to the capacity for clay particles to retain water in the soil matrix (Rowell 1994, 21).

Topsoil water content was mapped across the site using ranges to identify patterns of content (figure 101). There is a clear distinction in water content with topography on the site. All water contents less than 15% lie at points higher than 67m AOD, predominantly to the western end of Field C where the land rises to 69.25m AOD. Soil with water contents of 15% and above reside in the central down slope area of Field C, and across fields B and A. This is likely to be linked to soil type as well as topography. As discussed in section 5.4, down slope areas of the site are prone to waterlogging and contained former water features in the landscape, suggesting a high water table. Greatest variation in water content is observed in Field C, mainly due to changes in slope. There is a very slight trend for conductivity to increase as water content increases, as shown in figure 102. This corresponds with higher water content and higher conductivity levels present in down slope areas of the site.

As discussed in section 2.3.3.6, soils with water contents above 20% should be deemed aggressive. With an average topsoil content of 15.90% and only four samples recorded over 20%, water content across the site is not particularly high or at aggressive levels for the corrosion of lead.

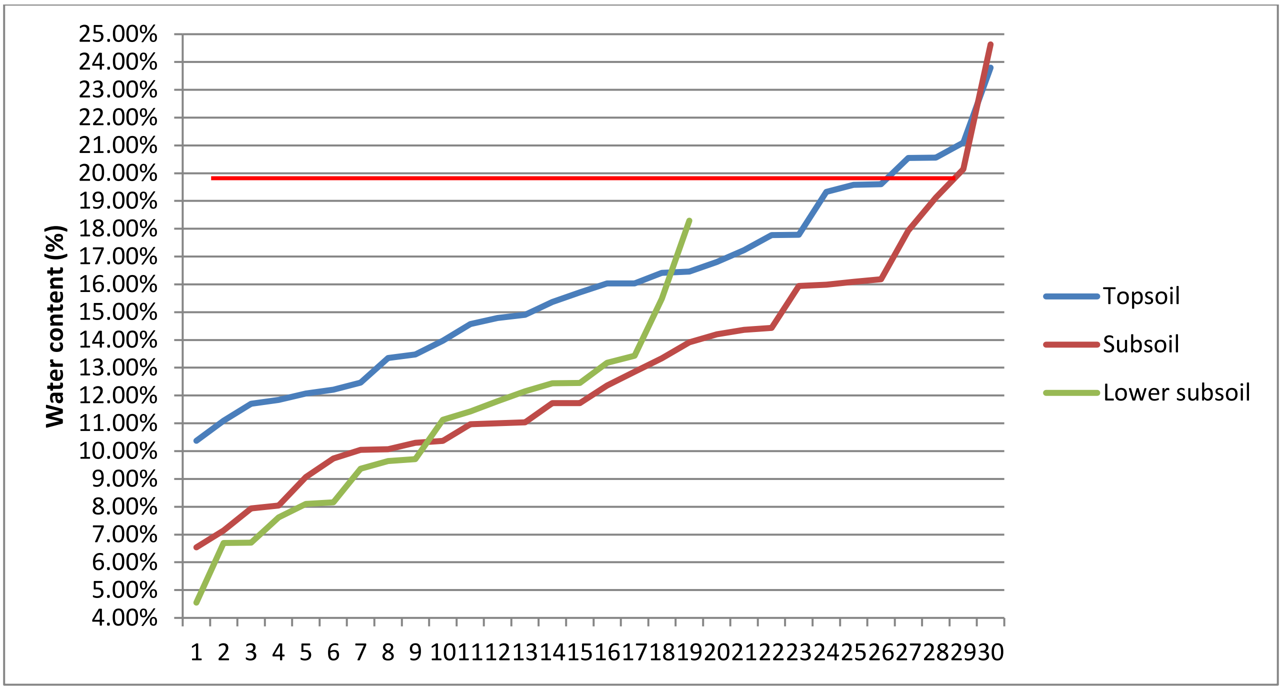


Figure 100: Water content of all soil samples by soil layer, by percentage content. Above the red line indicates when water levels should be deemed potentially aggressive, at 20% and above.

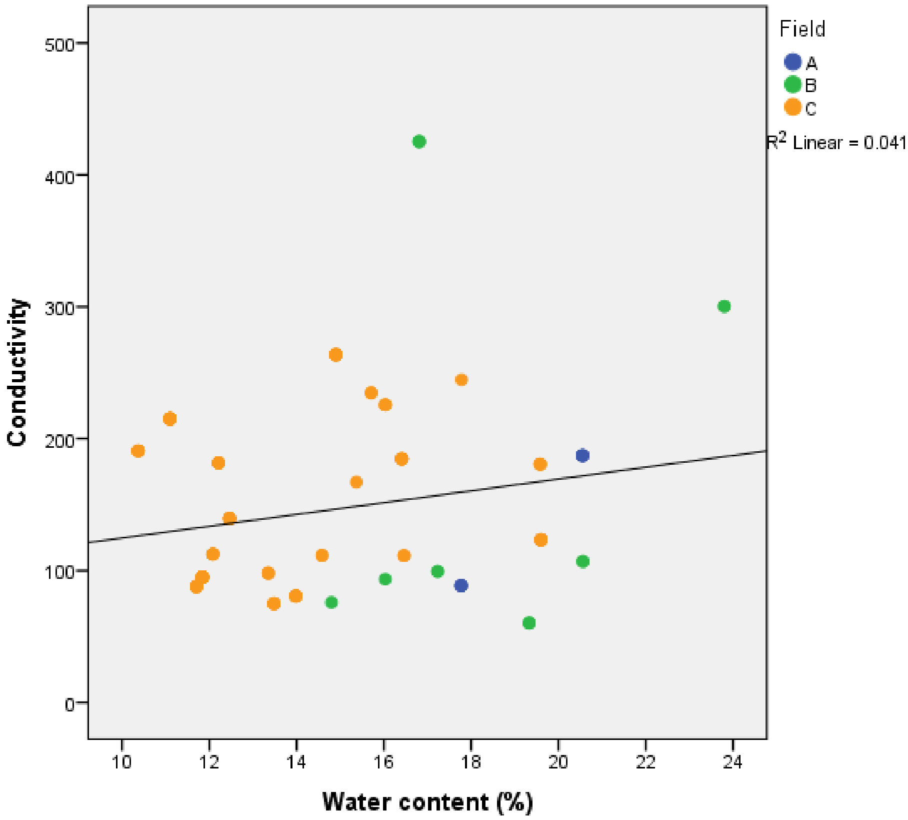


Figure 101: The relationship between water content and conductivity of soil, indicating little trend for conductivity to increase as water content increases.

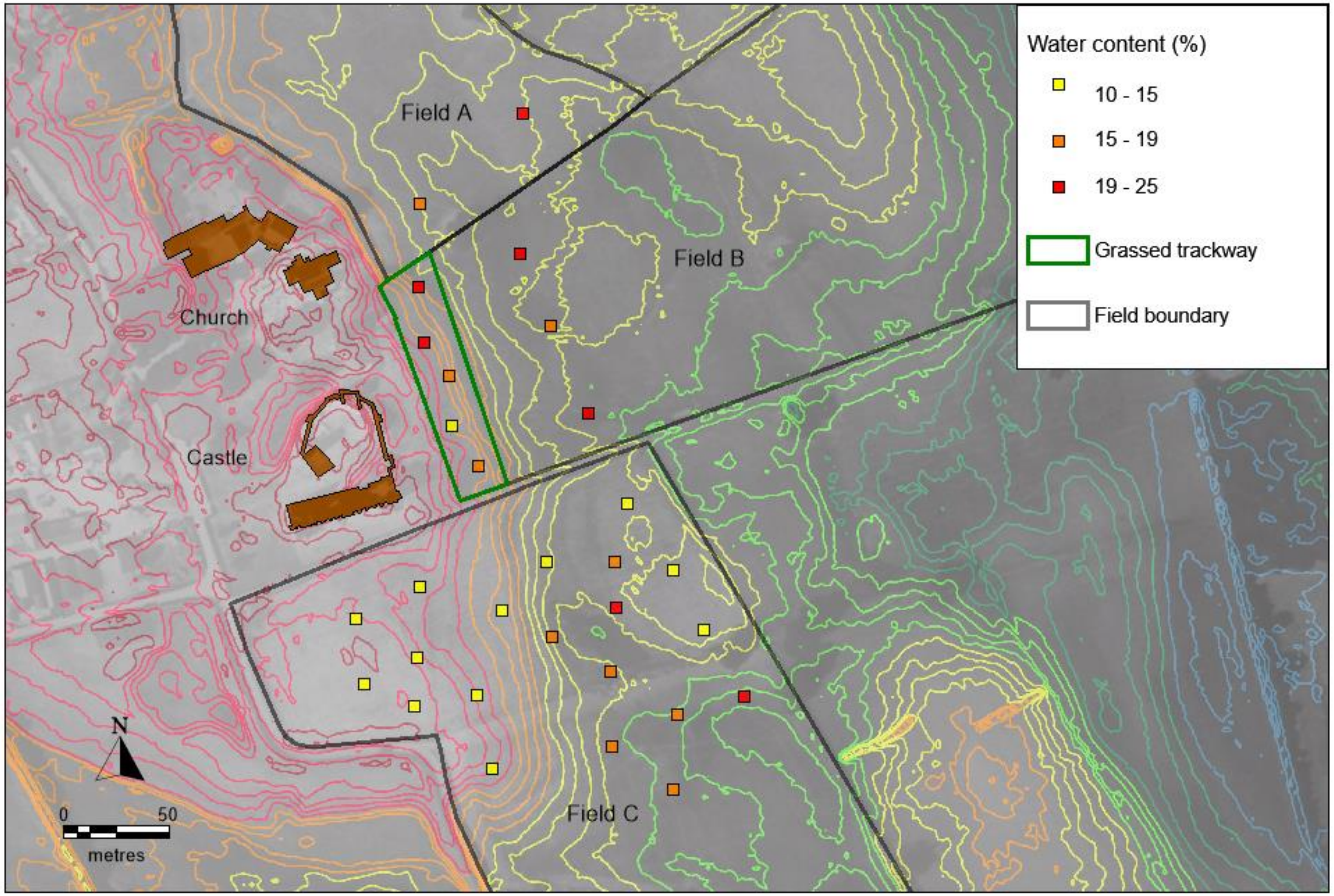


Figure 102: Distribution of water content in topsoil samples across the site, highlighting lower water levels upslope and higher water levels downslope. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

5.7.3.1 Water content against bullet condition

As discussed above, water content increases in lower areas of the site. When the water content of the soil is statistically compared to the condition of bullets, there is no trend present (figure 103). This lack of trend is supported by the correlation coefficient of 0.051 which is not significant (table 38). This graph does show however, that water levels tend to be higher in fields A and B compared to C. Field C contains a raised plateau where the formal gardens of the estate resided and is significantly drier than other areas of the site. Even though there is no clear trend across the site as a whole, patterns do emerge when each field is discussed in turn in relation to water content in section 5.8.

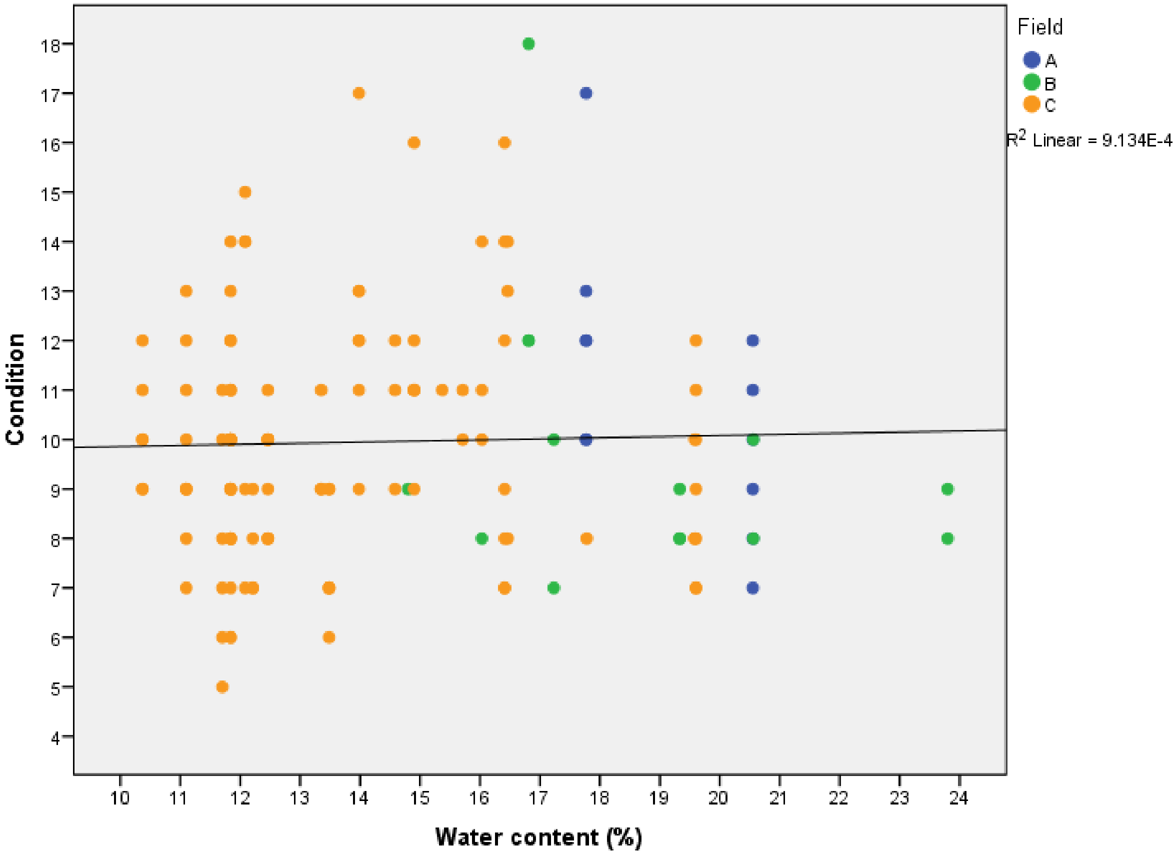


Figure 103: Scatter plot showing the water content of soil against the condition of bullets, showing no clear trend.

			Condition	Water
Spearman's rho	Condition	Correlation Coefficient	1.000	.051
		Sig. (2-tailed)	.	.545
		N	143	143
	Water	Correlation Coefficient	.051	1.000
		Sig. (2-tailed)	.545	.
		N	143	143

Table 38: Spearman's rank correlation coefficient between the water content of soil and the condition of bullets. A value of 0.051 indicates no significant correlation.

5.7.4 Organic content results

Organic content of soils across the site ranges from 0.77% to 11.33%, with consistent higher levels in topsoil. Organic content in topsoil ranges from 4.74% to 9.41% with an average of 6.17±0.01%. Though organic levels average higher in topsoil deposits, there is greater range of organic content in lower deposits (figure 104). Subsoils range from 0.81% to 11.33% with an average of 4.02±0.02%. Lower subsoils range from 0.77% to 7.57% with an average of 2.53±0.01%. It is evident that organic content gradually decreases with soil depth across the site (figure 105).

Soils rich in organics would tend to have a higher organic matter content, with up to 25% organic content (Brady and Weil 2002, 500; Hodgson 1978, 201). Moreton Corbet soils are therefore not high in organics. Defra suggest that organic matter content over 10% should be deemed an organic soil (see section 2.3.3.7). All Moreton Corbet topsoil samples were consistently below 10% and therefore are not deemed organic or aggressive in terms of organic matter content.

Soils were mapped across the site in terms of their levels of organic content (figure 106). Organic content corresponds well with water content, particularly in Field C, as similar areas of higher organic content are also high in water content, indicating an improved soil structure. Organic matter forms a part of the colloid fraction of the soil which enables the absorption and retainment of water in the soil column (see section 2.3.3.3). The graph shows (figure 107) there is a slight positive correlation with water content increasing as organic content increase, which is supported by the correlation coefficient value of 0.409 which is statistically significant (table 39).

The highest organic content from the site measures 9.41% recorded in test pit 4 in Field B. This is perhaps an anomaly as the other four test pits in this area of the field averaged at 5.46% organic content which is lower than the site average of 6.12%. Organic contents higher than 6% tend to cluster to the eastern side of Field C, with levels lower than 6% predominating the western end of Field C and Field B. Fluctuations in organic content across the site could be down to crop growth, timing of fertilising, applications of manure and microbial activity, though organic levels are not particularly high in any areas of the site.

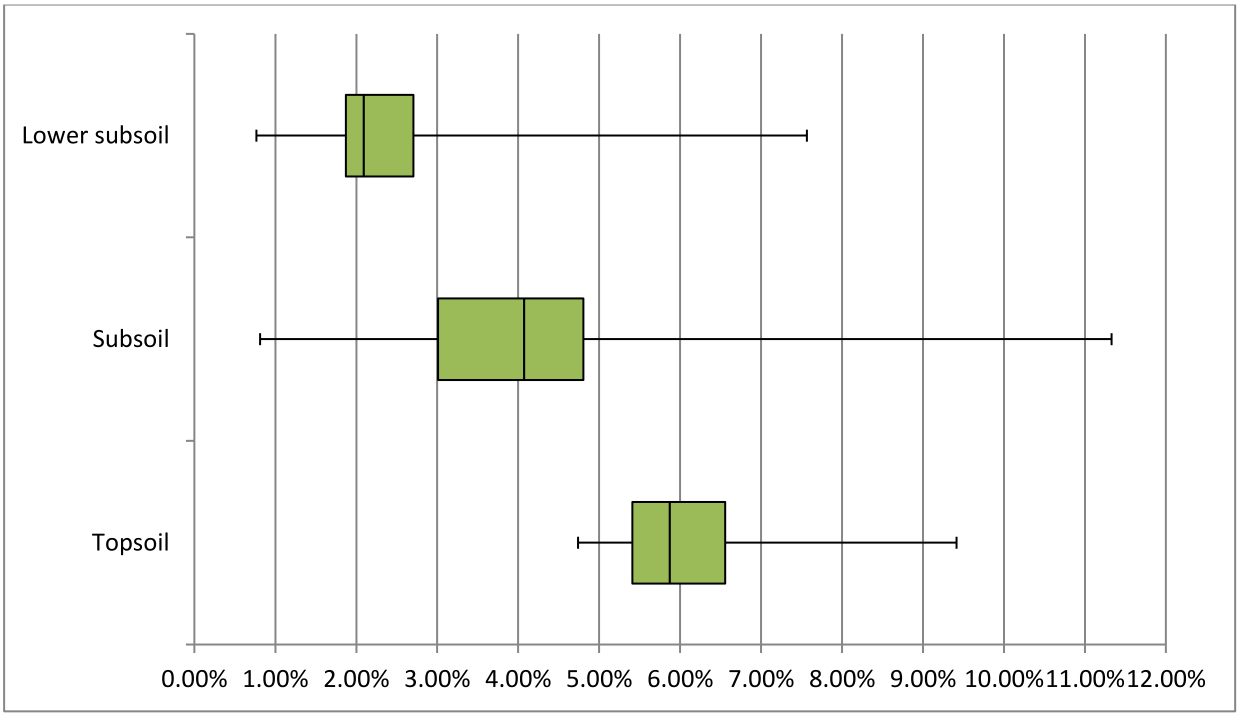


Figure 104: Box plot of organic content (%) of all soil layers from Moreton Corbet.

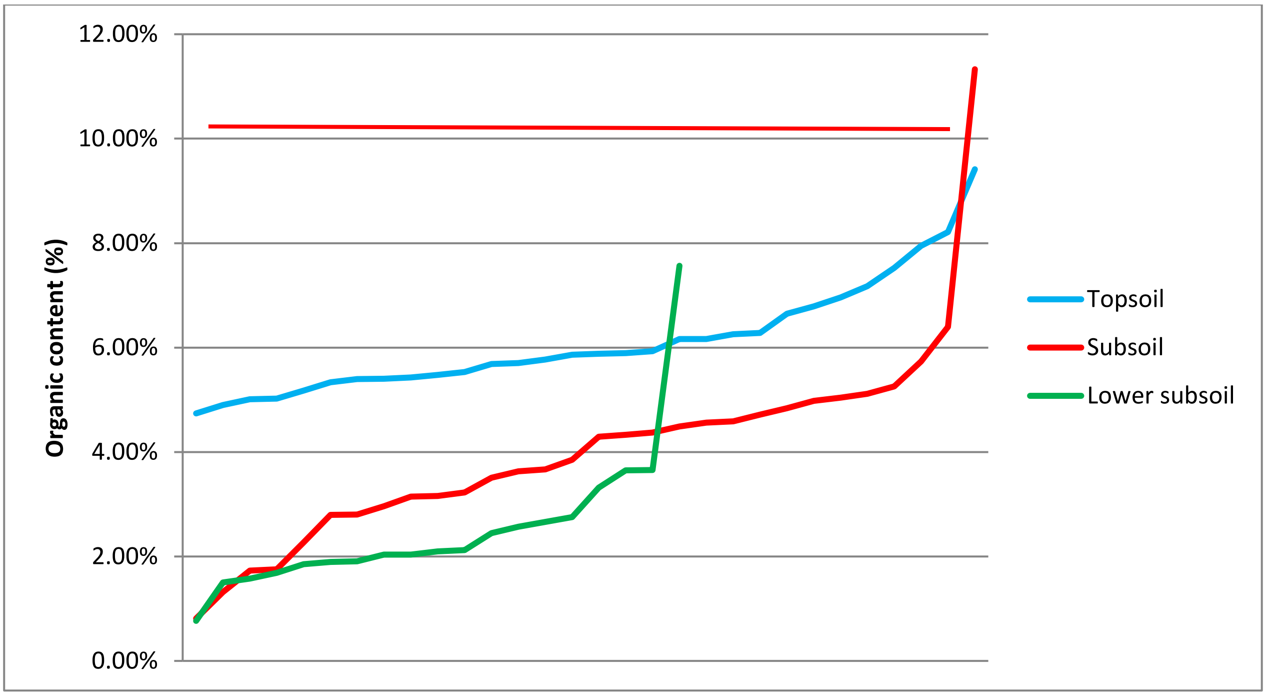


Figure 105: Organic content (%) by soil layer indicating a corresponding decline in soil depth. The red line indicates when a soil can be considered 'organic'.

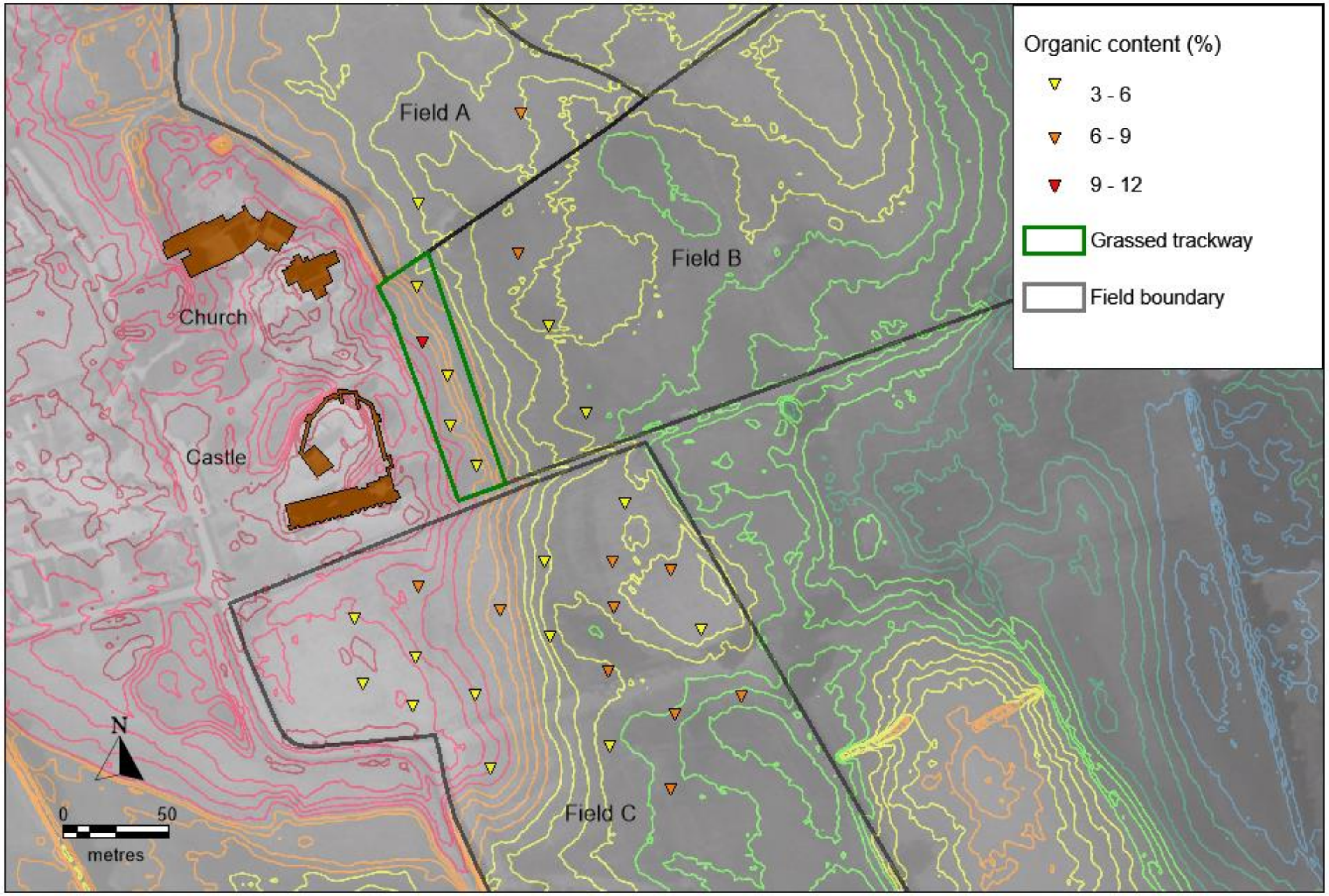


Figure 106: Distribution of organic content in topsoils across the site. Areas with lower % contents tend to cluster in topographically higher areas of the site. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

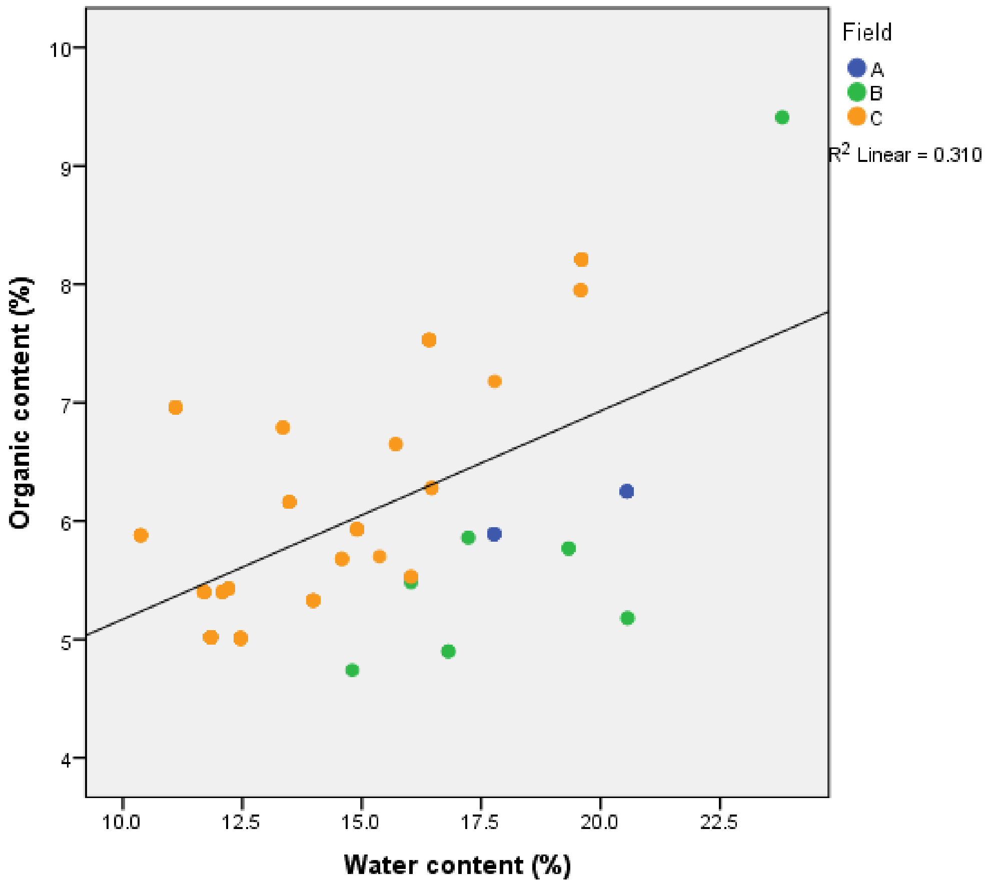


Figure 107: Relationship between water content and organic content of the soil, showing a slight positive correlation.

			Water	Organic
Spearman's rho	Water	Correlation Coefficient	1.000	.409**
		Sig. (2-tailed)	.	.000
		N	143	143
	Organic	Correlation Coefficient	.409**	1.000
		Sig. (2-tailed)	.000	.
		N	143	143

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

Table 39: Spearman's rank correlation coefficient for water content against organic content. The coefficient of 0.409 is significant showing a slight positive correlation.

5.7.4.1 Organic content against bullet condition

As discussed above, organic matter content of the soil across the site is not particularly high. When comparing the organic content against the condition of bullets, there is no clear trend, as would be expected from the relatively low organic content (figure 108). The correlation coefficient reveals a slight negative correlation, but the coefficient value of -0.085 is not significant (table 40).

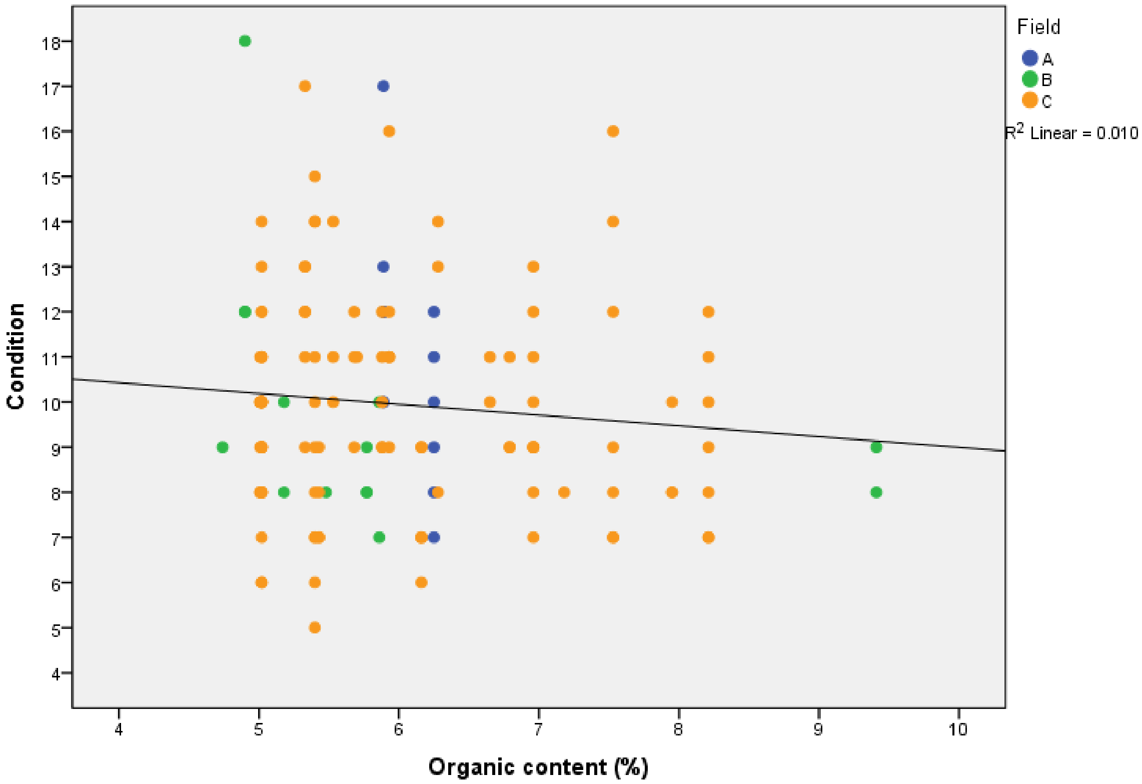


Figure 108: Scatter plot showing the organic content of soil against the condition of bullets, showing no clear trend.

			Condition	Organic
Spearman's rho	Condition	Correlation Coefficient	1.000	-.085
		Sig. (2-tailed)	.	.312
		N	143	143
	Organic	Correlation Coefficient	-.085	1.000
		Sig. (2-tailed)	.312	.
		N	143	143

Table 40: Spearman's rank correlation coefficient of -0.085 for the relationship between the organic content of the soil and the condition of bullets. This correlation value is not significant.

5.7.5 Texture results

Texture was recorded in the field using a texture classification chart. Samples were also analysed in the laboratory using a Malvern Mastersizer 2000 (see section 4.5.1.2). Comparing the results of both methods reveals significant differences. Using the laser diffraction method, 78% of the data lies within either sandy loam or clay loam texture classes, with the remaining 22% covering five other texture classes (figure 109). There is greater variation in the field with the greatest number of samples recorded as sandy silt loam (34%) and sandy clay loam (19%), with the remaining 47% covering seven further texture classes (figure 110).

Figure 111 depicts the differences in texture results from the two methods by presenting the data on the texture triangle. Even though the field observations vary from the Mastersizer results in terms of textural classes, the majority are recorded as bordering textural classes. Soils recorded as sandy clay loams in the field were usually recorded as sandy loams or clay loams in the laboratory. Soils recorded as sandy silt loams in the field were usually revealed to be sandy loams by the Mastersizer. This indicates that, though allocating textural classes in the field can give an indication of basic texture, it is not an accurate method and should always be done using a more reliable laboratory method. In this case there was an issue of identifying between the four main classes of sandy clay loam, clay loam, sandy loam and sandy silt loam, which in reality feel very similar to the touch and are difficult to differentiate by hand with certainty. The main benefit of using the laser diffraction method is obtaining accurate percentages of sand and clay particles in each sample to assess the effect sand and clay ratios have on the preservation of materials.

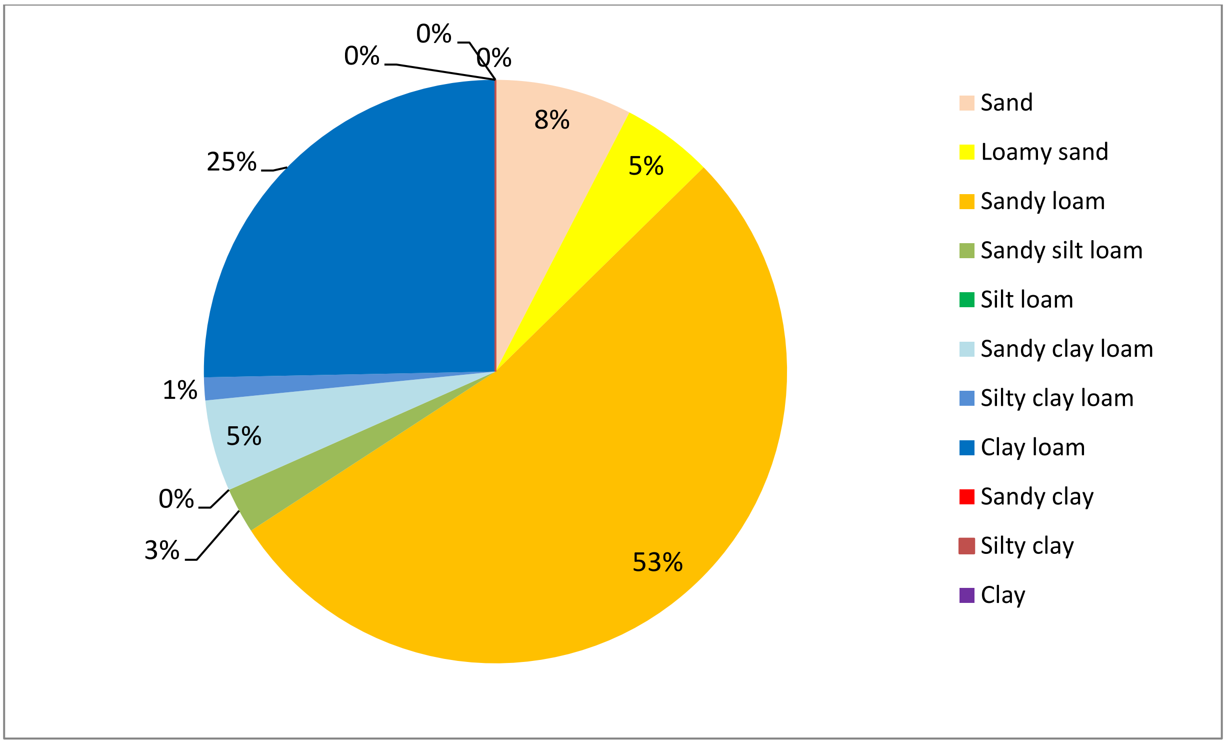


Figure 109: Texture classes of Moreton Corbet soils from Malvern Mastersizer in order of sands, silts and clays.

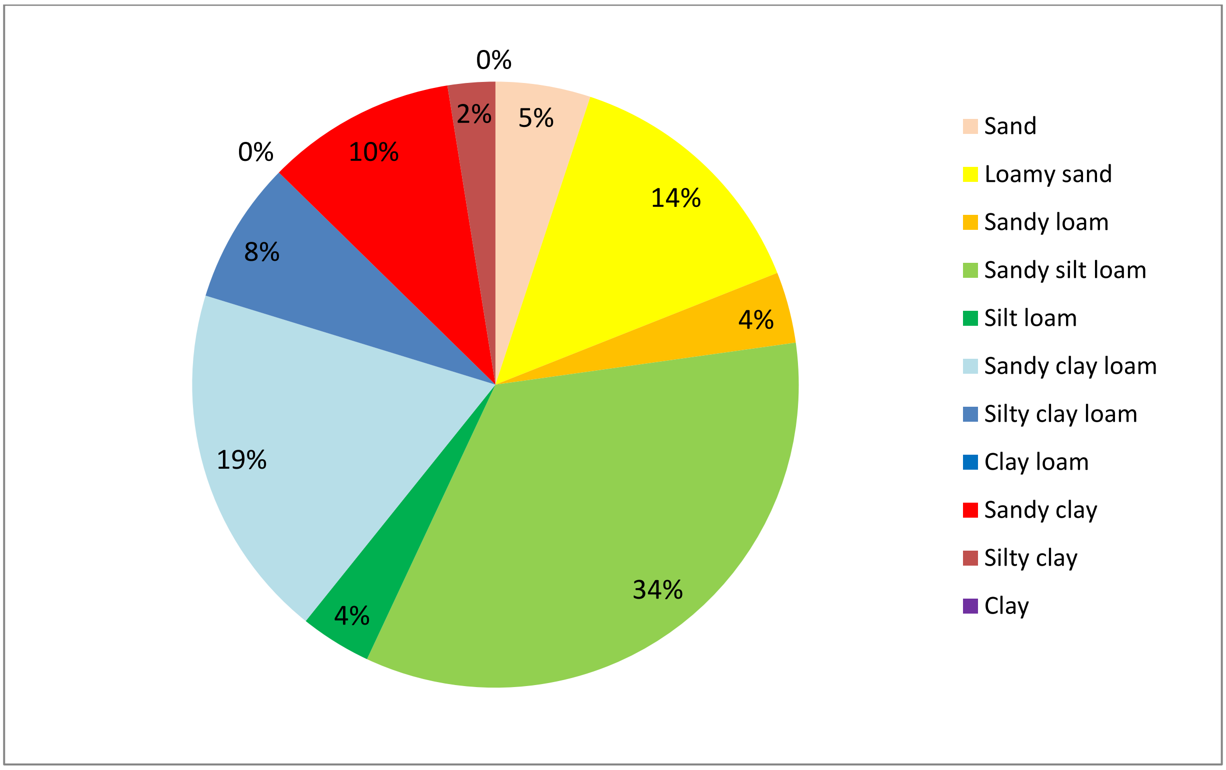


Figure 110: Texture classes of Moreton Corbet soils from field observations in order of sands, silts and clays.

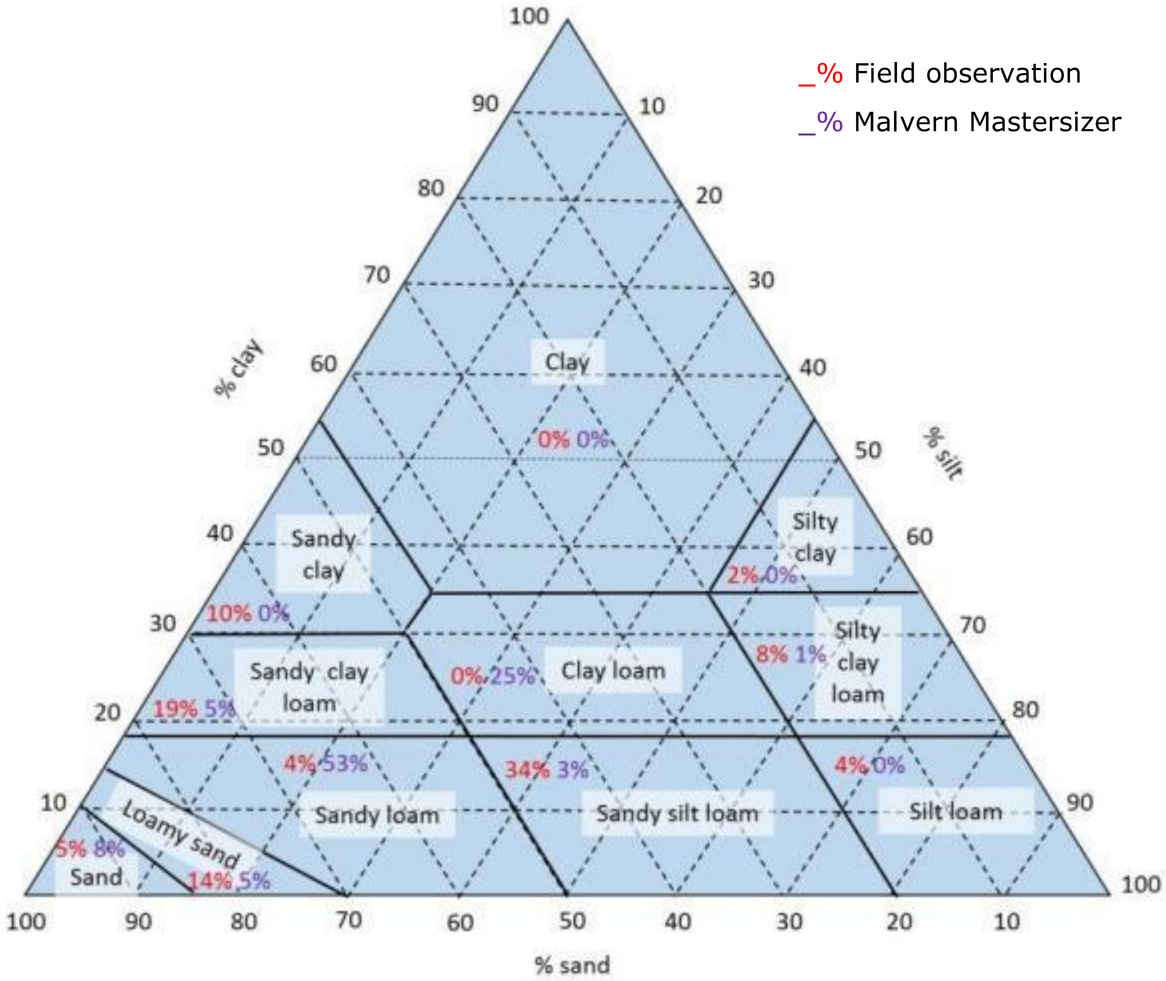


Figure 111: Texture classification triangle showing percentage of results of soil texture classes using field observations versus laser diffractometer.

There is moderate change in texture across the site from an area measuring only approximately 500m^2. 78% of the soil samples tested lie within the classes sandy loam or clay loam and this dominance continues throughout the soil column, though 'sand' appears more frequently in lower subsoil deposits in certain areas of the site (figure 112). There is much less variation in textural classes in subsoils, and lower subsoils only cover the range of sand, sandy loam and clay loam. It is important to consider soil texture throughout the soil column as the topsoil is composed partly of parent material from lower deposits and becomes replenished with soil from further down the soil column during cultivation episodes. Therefore the contents and texture of the lower soil levels will have an impact on the composition of the topsoil.

The majority of soil samples in every soil horizon from the site are a type of loam. Loams consist of a fairly even distribution of particle sizes and the best combination of physical and chemical properties in terms of crop production. Loams tend to drain easily whilst maintaining good water retention and a good supply of nutrients to plants (Rowell 1994, 20). Sandy loams have a greater proportion of sand particles and the same can be said for clay in clay loams, though significantly less clay is needed for a soil to be classed as clay. For instance, sample D100 is a clay loam even though its clay content is 21.27% and sand content is 39.67% (figure 113). Sample J100 is a sandy loam with a sand content of 64.97% (figure 114), indicating that much more sand is required for this texture class to dominate. This is due to the significant effect of the clay fraction on the physical and chemical properties of soils (see section 2.3.3.2).

66% of samples from the site were classed as a sandy soil, with 53% being a sandy loam with at least 50% sand content. 25% of the samples were classed as clay loams, with 20-30% clay content. This increase in clay content makes these soils firmer, have higher organic content and able to retain more moisture in the soil column. As figure 115 shows there is a correlation as clay content of soil increases, water content increases accordingly. This is due to the water retention capacity of clays due to its small particles tightly packed together and the attractive forces between charged particles. This correlation has a value of 0.583 which is statistically significant (table 41).

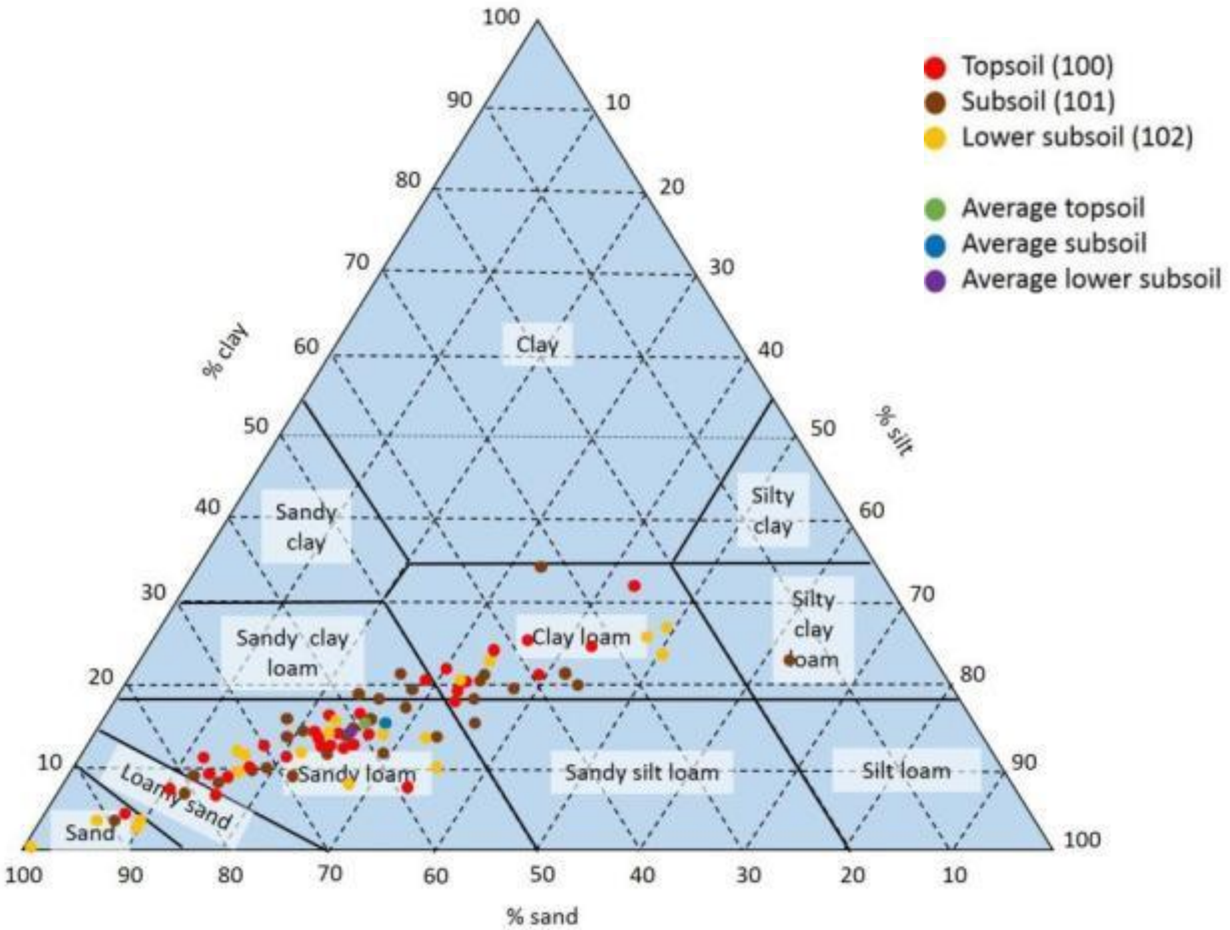


Figure 112: Texture triangle for all samples from the site by soil layer.

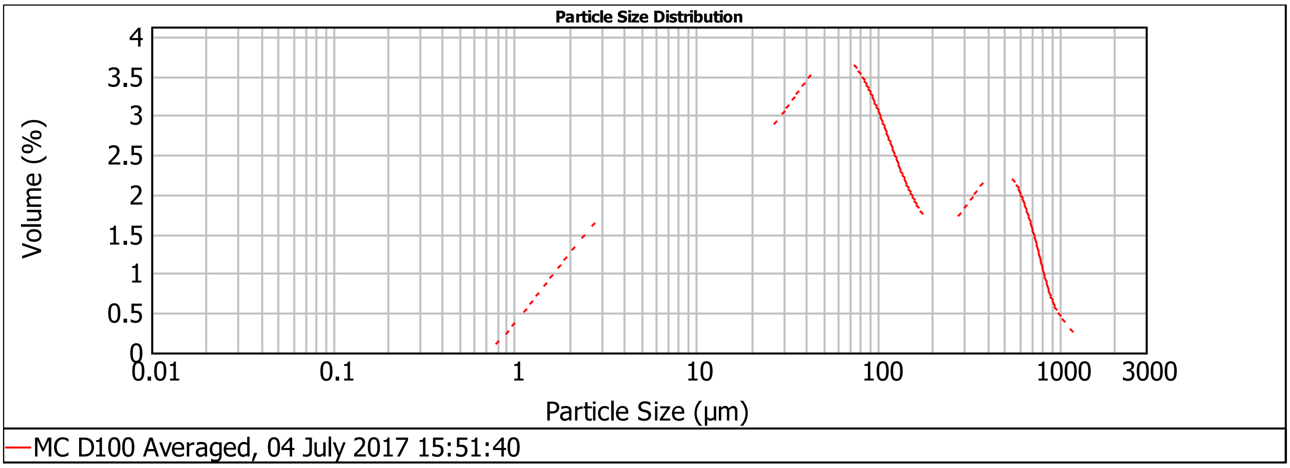


Figure 113: Particle size distribution results for topsoil D100, showing large proportion of smaller particles (i.e. clays and silts).

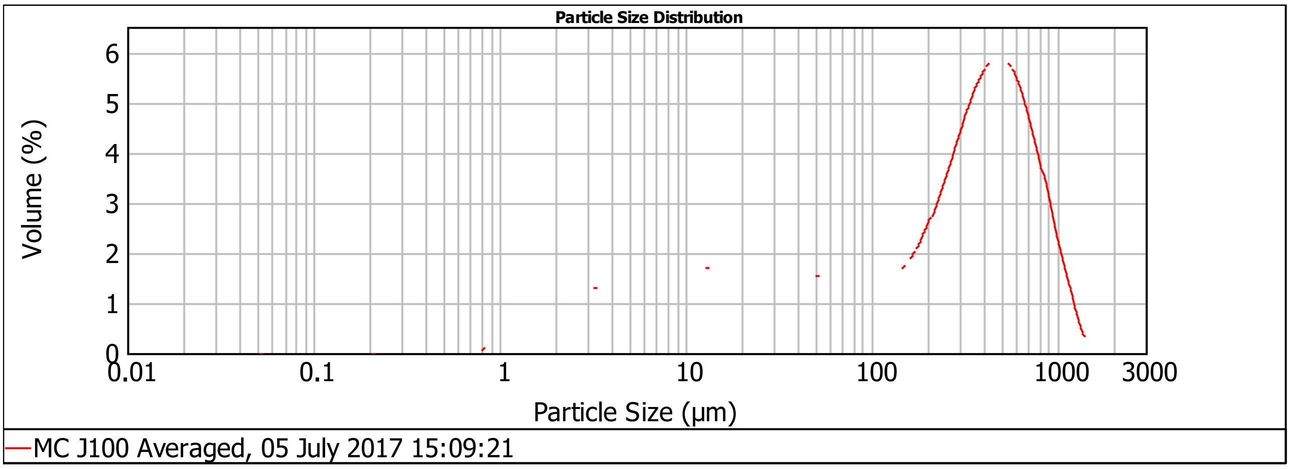


Figure 114: Particle size distribution results for topsoil J100, showing large proportion of larger particles (i.e. sands).

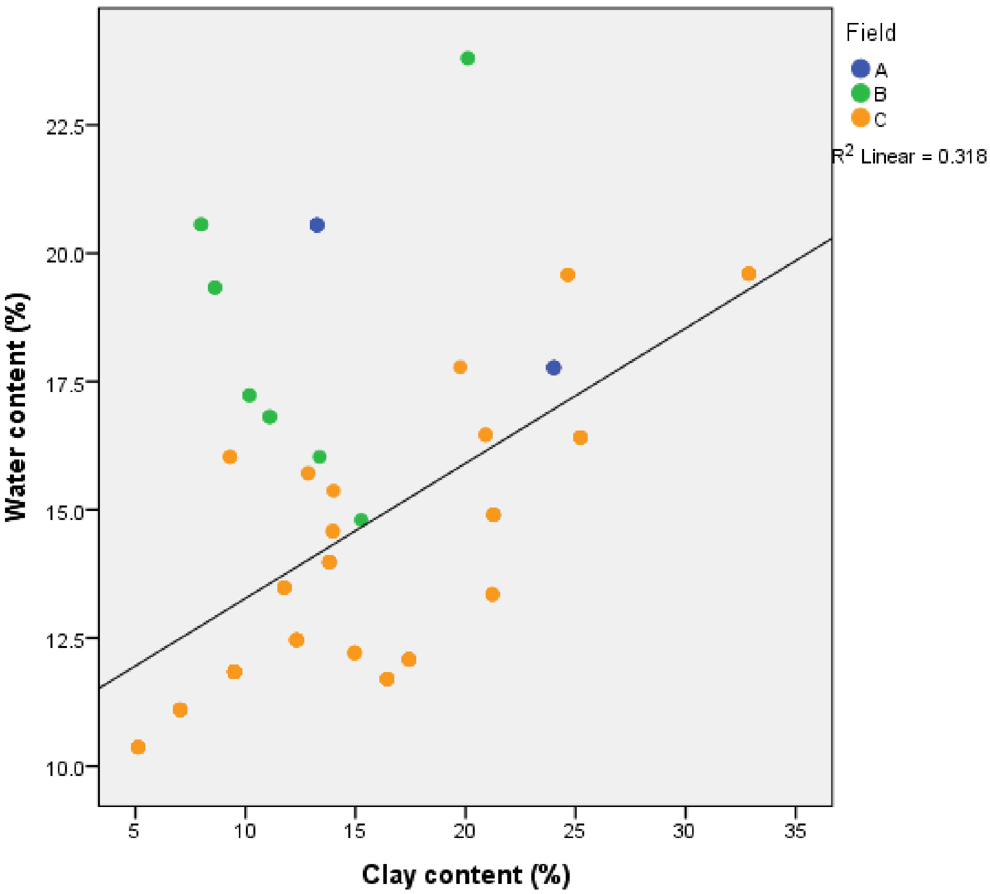


Figure 115: Scatter plot showing the relationship between water content and clay content of soil samples, revealing a positive correlation.

			Water	Clay
Spearman's rho	Water	Correlation Coefficient	1.000	.583**
		Sig. (2-tailed)	.	.000
		N	143	143
	Clay	Correlation Coefficient	.583**	1.000
		Sig. (2-tailed)	.000	.
		N	143	143

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

Table 41: Spearman's rank correlation coefficient for water content with clay content showing a significant positive correlation of 0.583.

As discussed in section 2.1, there has been disagreement over which texture classes promote or inhibit the preservation of lead in soils. Most research has agreed that sandy textures are worst for the preservation of metals (Tylecote 1979; Kibblewhite, Toth, and Hermann 2015), though clays do provide a large amount of reactive surface in the soil column to react with ions in the soil solution and are especially aggressive when acidic (Gilbert 1946). However, clays have poor aeration due to their small particle size and tight structure (Rowell 1994, 19-20). It is likely that sandy textures create a more inhospitable environment in terms of physical damage to objects water flows more rapidly between sand particles and they are abraded and churned in the soil, whereas clays may be more chemically damaging if their surfaces are reacting in solution in acidic environments.

The texture of the topsoil was mapped to display the distribution of textural classes across the site (figure 116). The topsoil and subsoil are very similar in textural distribution, with most areas being sandy loams. However, there is a distinct area in the mid to eastern end of Field C where an area of clay loam dominates. This area also corresponds with slightly higher water and organic matter contents, and with slightly higher pH levels. This also corresponds with bullets in poor condition, suggesting that the presence of clay loam in the soil may have had a negative impact on the preservation of the lead.

Based on the Ordnance Survey superficial geology map of the region (Ordnance Survey of Great Britain 1967), all collected data from the site lies on sands and gravels. However, from data collected in this study it is observed that boulder clay encroaches further into fields B and C than the superficial geology map suggests, with a significant area of boulder clay recorded in Field C (figure 117). This highlights the importance of taking samples in the field rather than relying purely on mapping evidence. This may be important when dealing with the preservation of metal artefacts as it appears that bullets are in poorer condition in areas of clay loams at Moreton Corbet.

5.7.5.1 Texture against bullet condition

Sandy textured soils are likely to have a negative impact on the preservation of metal artefacts due to their abrasive large surface areas and the ability of oxygen and water to pass through the soil column easily, promoting corrosion (Tylecote 1979; Kibblewhite, Toth, and Hermann 2015). Texture class compared to the condition of bullets was difficult to plot in a scatter diagram and shows no clear relationship (figure 118). A range of condition scores were recorded for all soil types present on the site and no clear trend is apparent. This is supported by the coefficient value of 0.084 which is not statistically significant (table 42).

However, as mentioned above, the condition of bullets deteriorates in areas of clay loams. This is perhaps surprising when sand content in theory would increase damage to bullets. However, it is likely due to the topography and nature of the site that bullets have been displaced down slope into the centre of Field C where higher water contents and seasonal flooding episodes are likely to accelerate their corrosion. On average, clay loams on the site contain 23.34±4.38% clay which may not be high enough to protect bullets from the abrasive nature of the sand particles which dominate the site.

As Gilbert's work showed, it is a combination of clay particles and acidity of soil which promotes a poor preserving environment for metals (Gilbert 1946). pH levels in the topsoil at Moreton Corbet ranged from 5.49 to 7.29, and though this is not particularly acidic, perhaps the areas of slight acidity and areas of clay have created a damaging environment for lead. As revealed in chapter 6, clay content at the site of Edgehill averages at 39.34±10.47% which is much higher than the samples recorded at Moreton Corbet. pH levels at Edgehill are also much higher than at Moreton Corbet, suggesting that the high clay content combined with alkalinity has aided the preservation of bullets. There is a suggestion therefore, that acidic clays would be the worst environments for lead to reside in. It would be very useful to assess an acidic clay site in future to verify this theory.

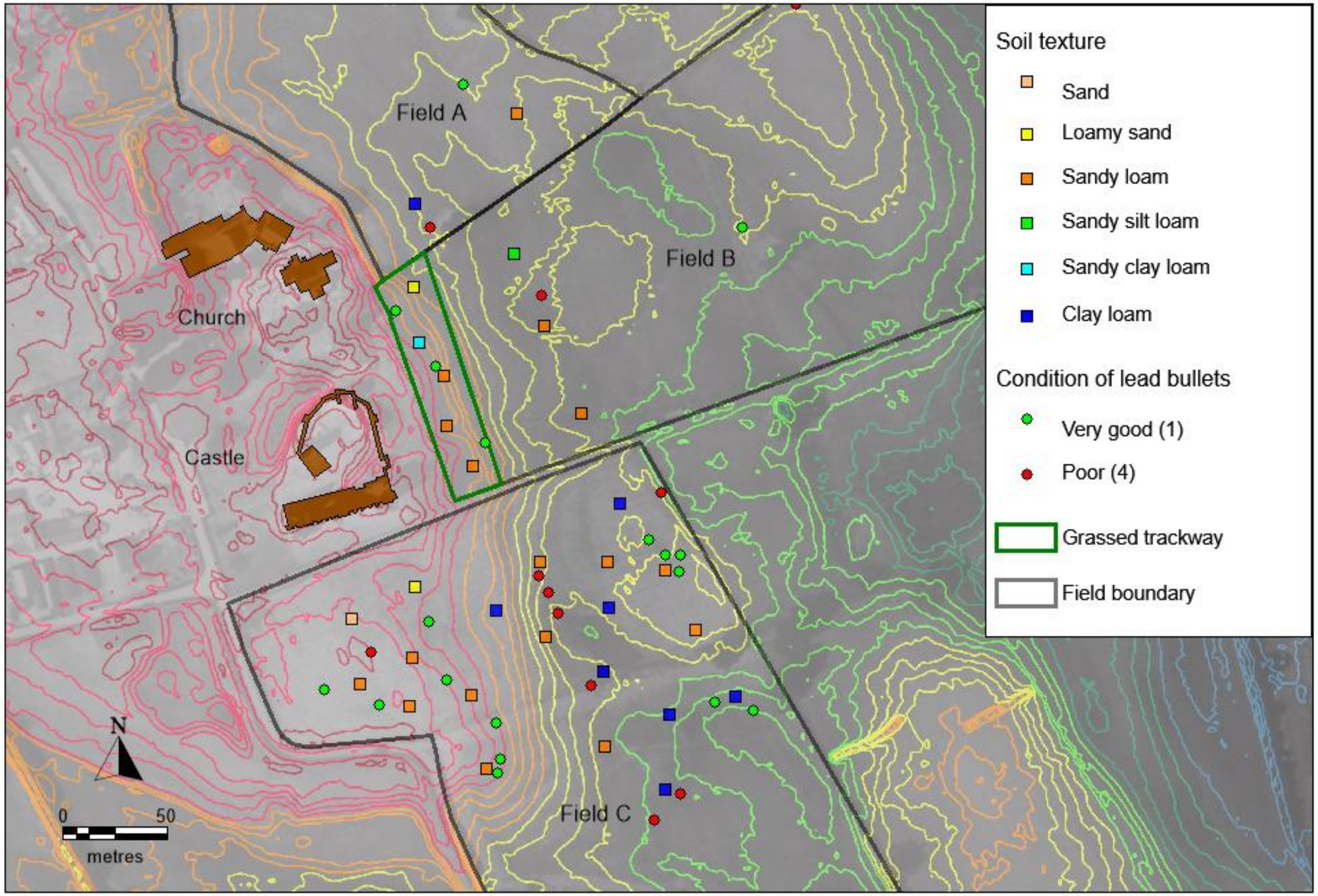


Figure 116: Distribution of texture classes across the site and the location of bullets in very good (1) and poor condition (4). Bullets in poor condition tend to cluster around areas of clay loam. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

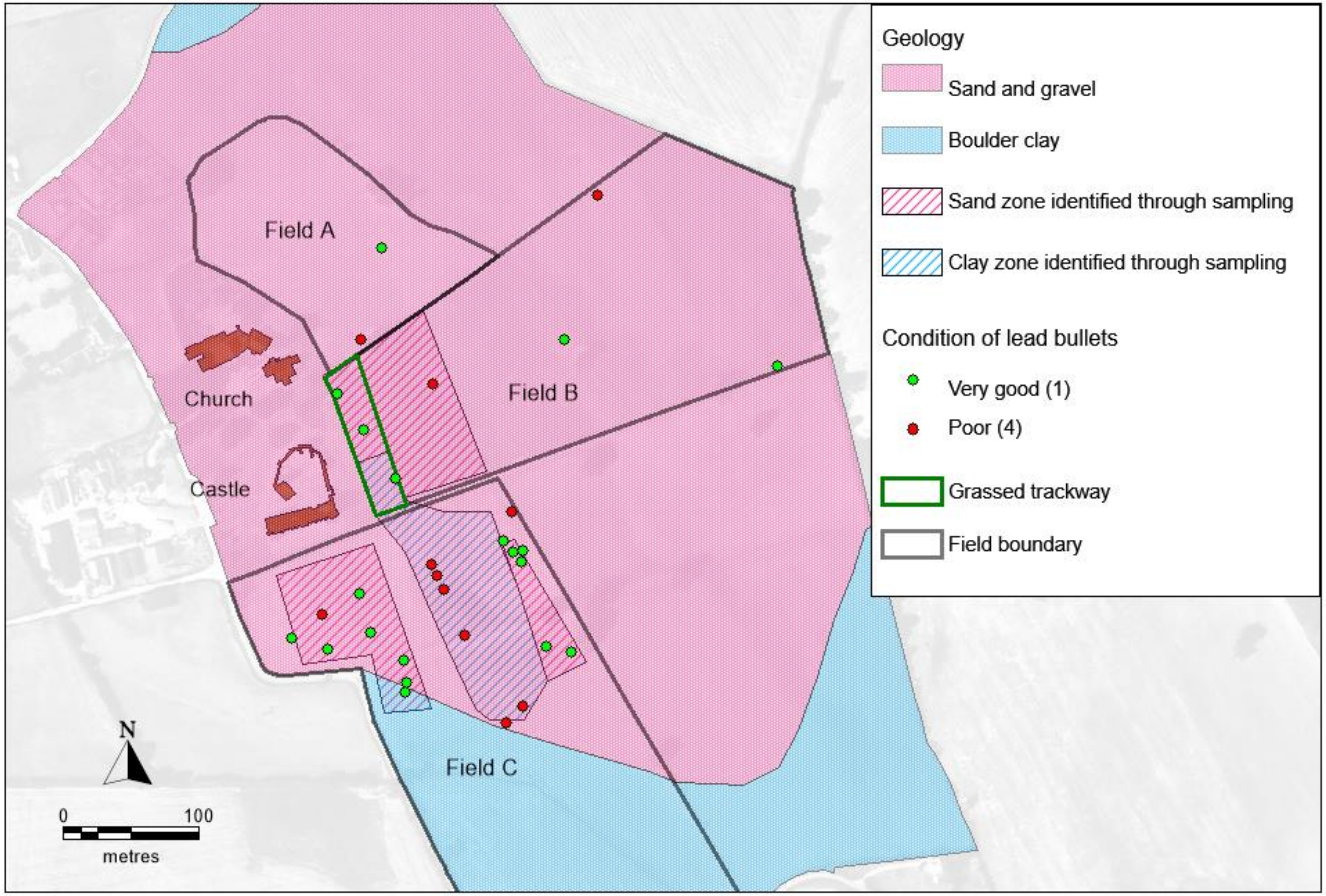


Figure 117: Comparison of Geological Survey boulder clay and sand boundaries with areas identified in this study. Bullets in poor condition appear to correspond with an area of clay in Field C. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service.

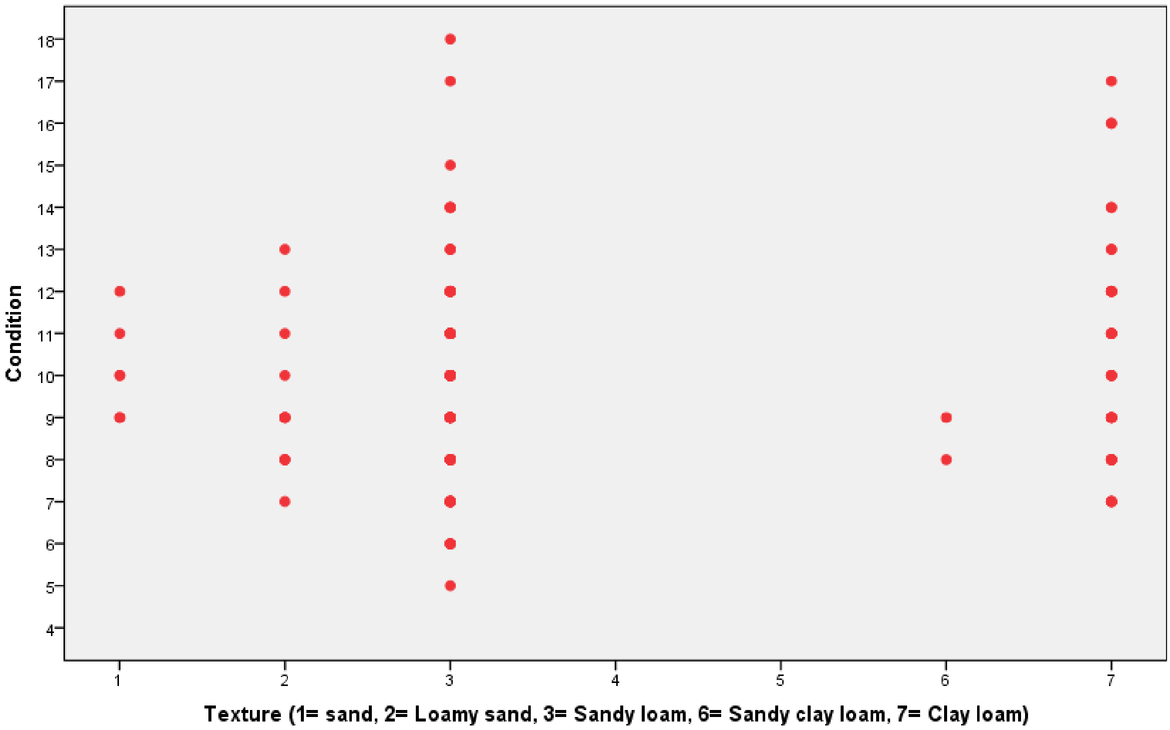


Figure 118: Scatter plot showing the texture class of soil against the condition of bullets, showing no clear trend.

			Condition	Texture
Spearman's rho	Condition	Correlation Coefficient	1.000	.084
		Sig. (2-tailed)	.	.316
		N	143	143
	Texture	Correlation Coefficient	.084	1.000
		Sig. (2-tailed)	.316	.
		N	143	143

Table 42: Spearman's rank correlation coefficient of 0.084 for the relationship between soil texture and the condition of bullets, which is not significant.

5.7.6 Nitrate content results

Nitrate levels were recorded in 9 out of the 22 test pits and were not collected for all soil samples. Recording nitrate levels was a later development in this study and as a consequence measurements were limited as readings take significantly longer than other laboratory tests. As discussed in section 2.3.3.9, nitrogen supply in soils varies, with average recommended levels for most soils being 50mg/kg, though this recommendation increases for loams and clays.

Nitrate content of soil at Moreton Corbet differ considerably between soil horizons. Topsoil levels are moderate to very high, ranging from 83.2mg/kg to 702.7mg/kg, with an average of 243.2±216.2mg/kg. These levels drop dramatically in the subsoil, which ranges from 12.6mg/kg to 124.3mg/kg, with an average of 62.9±35.7mg/kg. These levels drop again in lower subsoil deposits, which range from 8.6mg/kg to 73.2mg/kg, with an average of 36.7±26.5mg/kg (figure 119). It is not surprising that nitrate levels drop significantly with soil depth as nitrates are very soluble and mobile in soil solutions and much is lost from the column through leaching, run off and denitrification (Defra 2010, 24-25). However, levels are relatively high in the topsoil for certain areas of the site, indicating that levels remain high in the topsoil even with leaching in lower soil levels. It must be reiterated that these measurements are the result of one phase of sampling and ideally tests should be conducted regularly to reveal how levels vary throughout the year. It is likely that these levels will be much lower in winter when fertiliser is not being applied and crops are dormant.

Nitrate concentration was mapped across the site (figure 120). Average levels are much higher in Field C than Field B. Two measurements from Field C are particularly high from test pits B and F measuring 503.8mg/kg and 702.7mg/kg. There appears to be no pattern in terms of topography or soil type in nitrate levels, with high readings recorded in upslope and down slope areas and in areas of both sandy loams and clay loams.

Very little research has been conducted into what quantities of nitrates are required to cause a damaging effect on buried metals, though studies have shown their presence to be a factor in the deterioration of metals (Pollard *et al.* 2004; Sivilich 2016). It is assumed that the higher the concentration of nitrates, the greater risk of damage to buried metals, as lead is particularly vulnerable to nitric acid (see section 3.3.5). Field C exhibits highest nitrate levels and therefore poses the greatest threat to preservation. More readings would have to be conducted at the site over a number of seasons in order to gain more definitive results and conclusions.

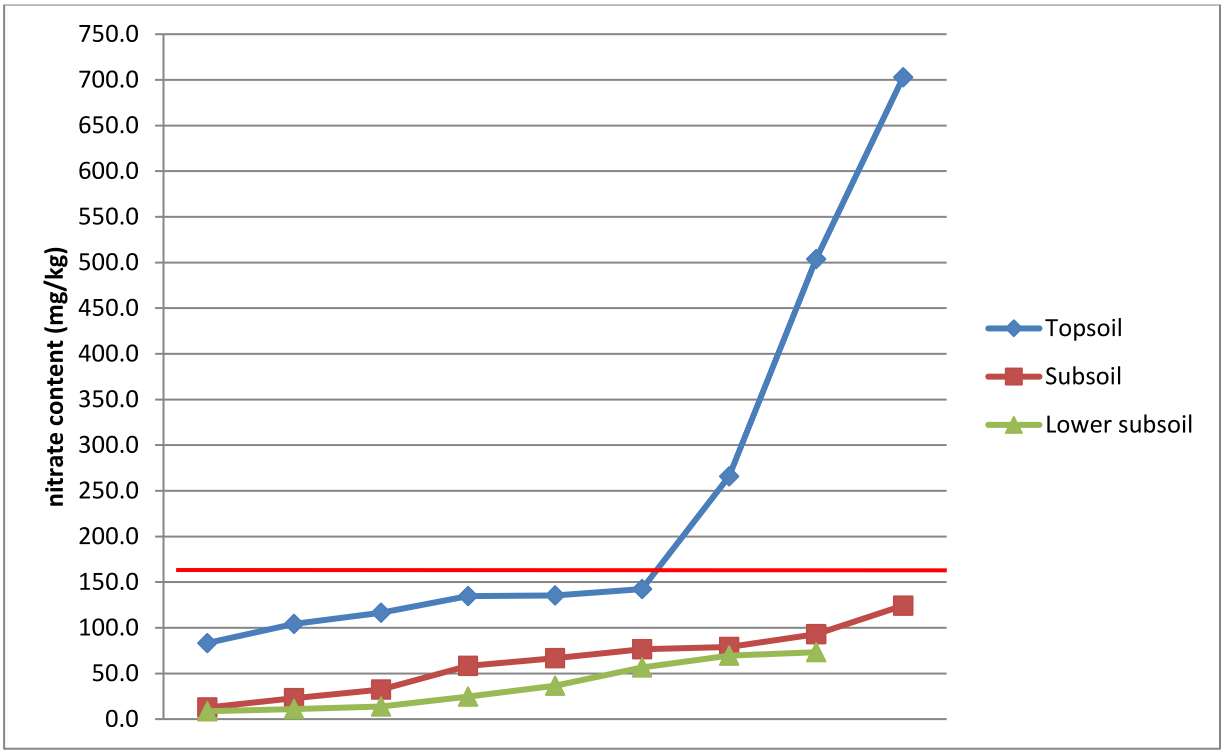


Figure 119: Nitrate concentration of soil layers across the site, indicating significantly higher levels in topsoil deposits. The red line indicates relatively high levels of nitrates for soils (Agricultural and Horticultural Development Board 2017).

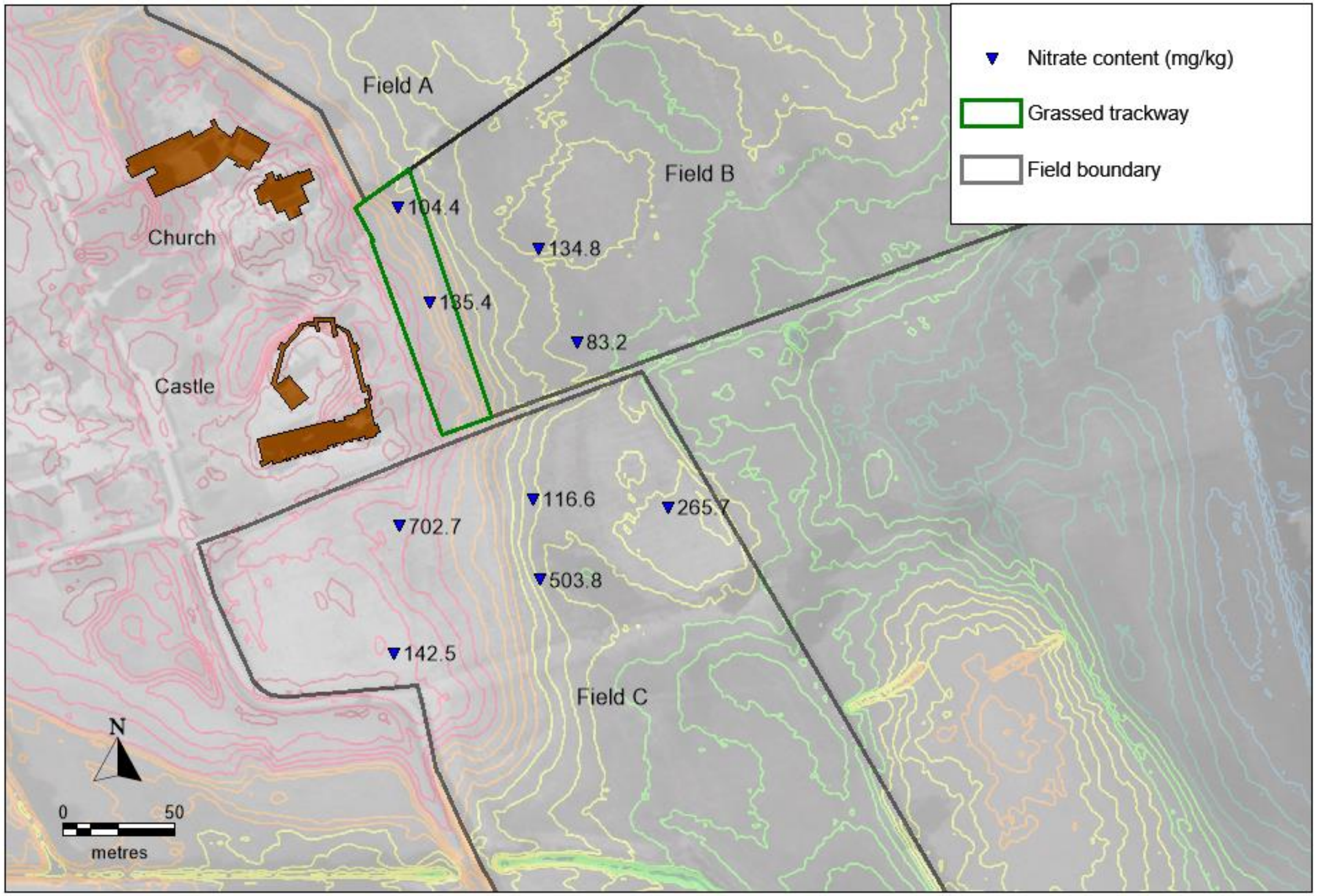


Figure 120: Nitrate concentration (mg/kg) of topsoil samples across the site, showing no clear trend. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

5.7.6.1 Nitrate content against bullet condition

The relationship between the nitrate content of the soil and the condition of bullets shows a very slight negative correlation. This is against predictions that as nitrate content increases the condition of bullets would deteriorate, suggesting they have not played a major role in the condition of bullets at this site (figure 121). This negative correlation however, is not statistically significant, revealed by a coefficient of -0.288 (table 43). Nitrate levels vary throughout the year and it is possible that their effect on corrosion rate is linked to pH. Nitric acid can have a damaging effect on metals, but this is formed through the oxidation of nitrogen or through the presence of atmospheric moisture and acid rain.

Three measurements taken from Moreton Corbet are however relatively high at 265.7, 503.8 and 702.7mg/kg. As stated above, more measurements would need to be taken throughout the year to fully address this correlation. Any corrosion triggered by an increase in nitrate content is likely to take place after nitrogen application on fields before it is leached out of the topsoil (Sivilich 2016).

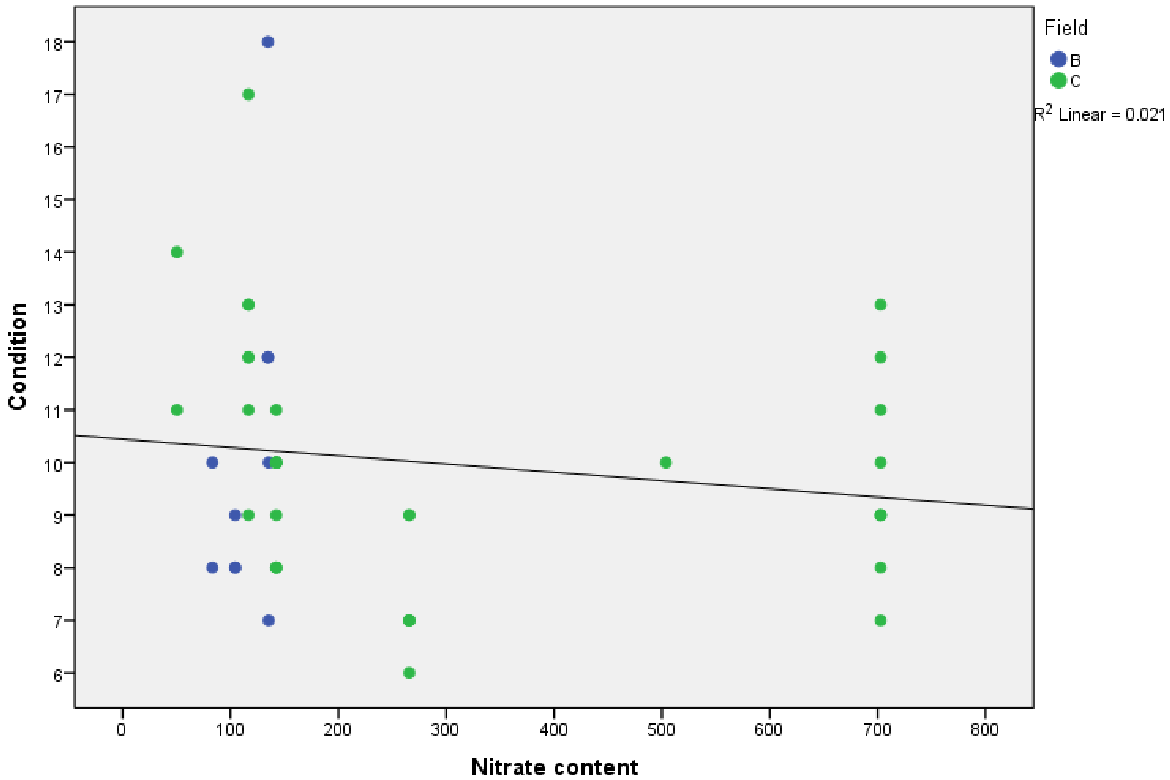


Figure 121: Scatter plot showing the nitrate content (mg/kg) of soil against the condition of bullets, showing slight negative correlation.

			Condition	Nitrate
Spearman's rho	Condition	Correlation Coefficient	1.000	-.288
		Sig. (2-tailed)	.	.058
		N	143	44
	Nitrate	Correlation Coefficient	-.288	1.000
		Sig. (2-tailed)	.058	.
		N	44	44

Table 43: Spearman's rank correlation coefficient of -0.288 between the nitrate content of soil and bullet condition, which is not statistically significant.

5.7.7 Chloride content results

Chloride content varies in topsoils from 30.75mg/kg to 120.36mg/kg, with an average of 85.41±27.19mg/kg. In subsoils this drops to 44.32 to 124.84mg/kg, averaging at 78.47±27.98mg/kg, and in lower deposits this drops again to 38.29-90.95mg.kg, averaging at 70.88±17.62mg/kg (figure 122). Chloride content in topsoils is significantly lower than nitrate levels in topsoils. The UK Soil Observatory (UKSO) has recorded chloride levels across the site between 93.08-96.87mg/kg which is just higher than the average recorded in this study (UKSO 2015). Levels across the site did not vary dramatically, with low levels across all fields (figure 123). It must be noted that the reliability of the chloride results in this study can be brought into question as all results were between 1 and 10ppm (see section 4.5.1.7.1). The low concentrations suggest that chloride levels are not high enough to cause significant damage to lead.

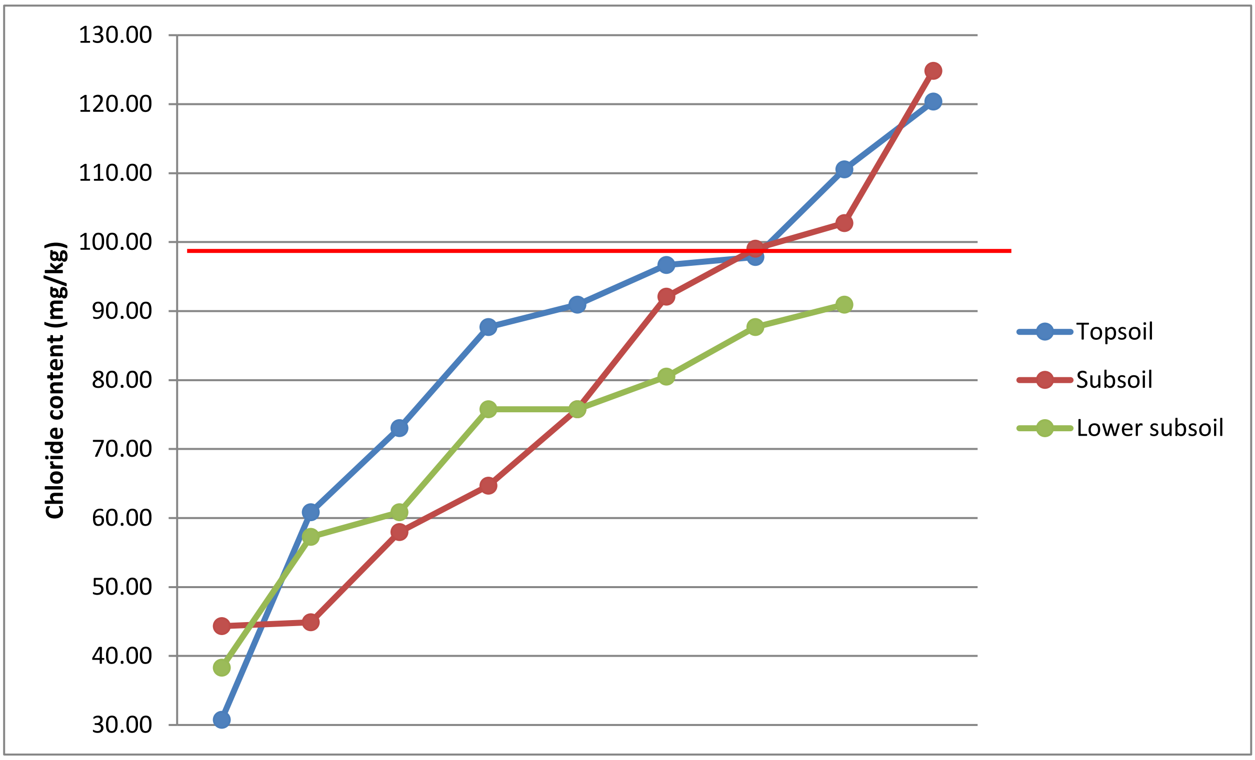


Figure 122: Chloride content of all soils sampled across the site. The red line indicates a moderate level of soil chloride.

5.7.7.1 Chloride content against bullet condition

The chloride levels in topsoils across the site are low to moderate for soil levels in the UK, though it remains unclear as to what concentration of chlorides is required to cause damage to buried metal artefacts (Pollard *et al.* 2004).

The relationship between the chloride content of the soil and the condition of bullets appears the strongest of all parameters at this site, revealing a slight positive correlation (figure 124). This indicates that as chloride content increases, there is a slight tendency for condition to deteriorate. However, the coefficient for this relationship is 0.291 and although higher than the results for other soil parameters, this is still not statistically significant (table 44). As stated above, the chloride levels in the soil were low to moderate. This relationship requires further investigation and would benefit from accelerated experiments where lead bullets are subjected to chloride concentrations under laboratory conditions (see chapter 9).

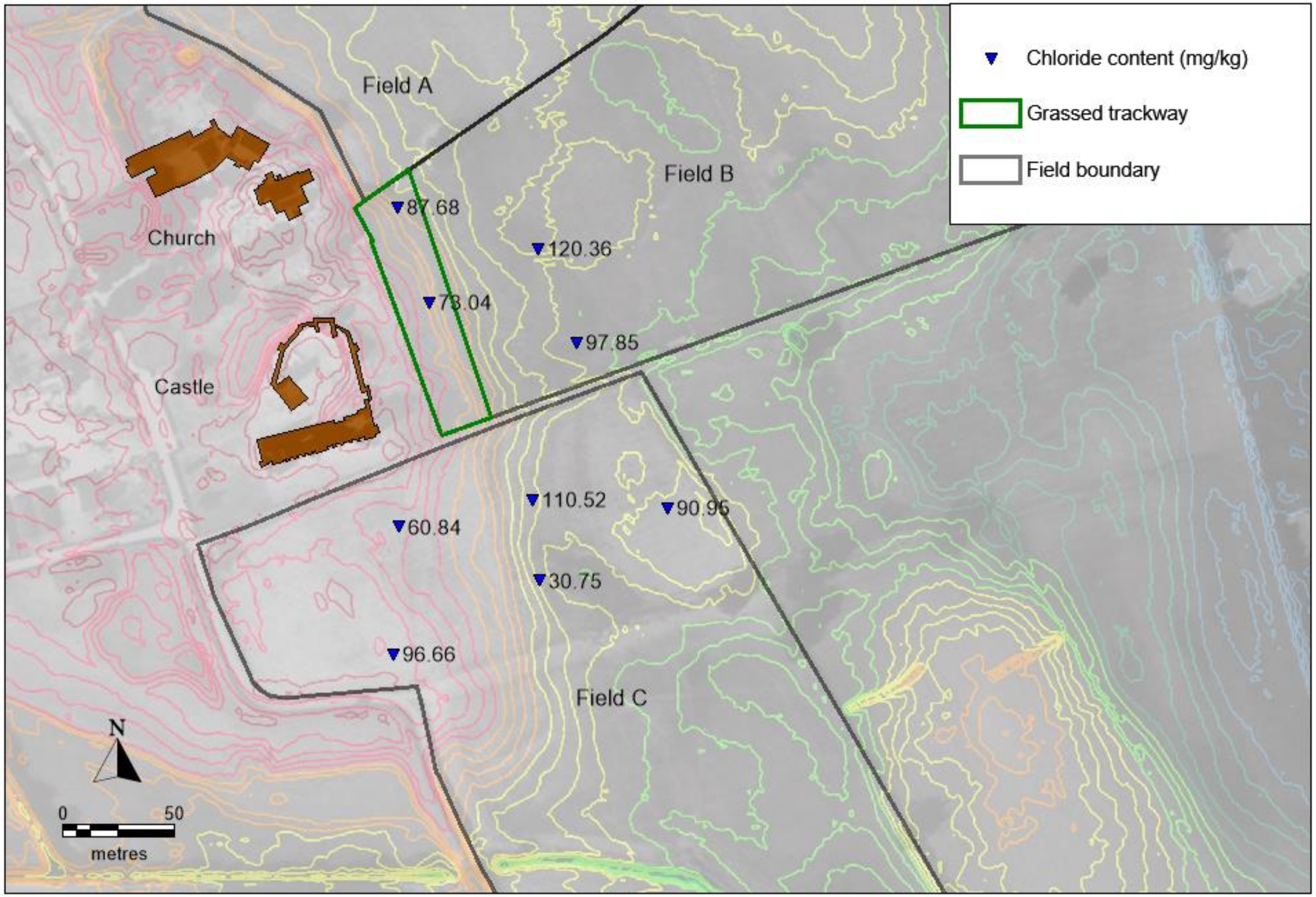


Figure 123: Chloride concentration (mg/kg) of topsoil samples across the site, showing no clear trend in concentration. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

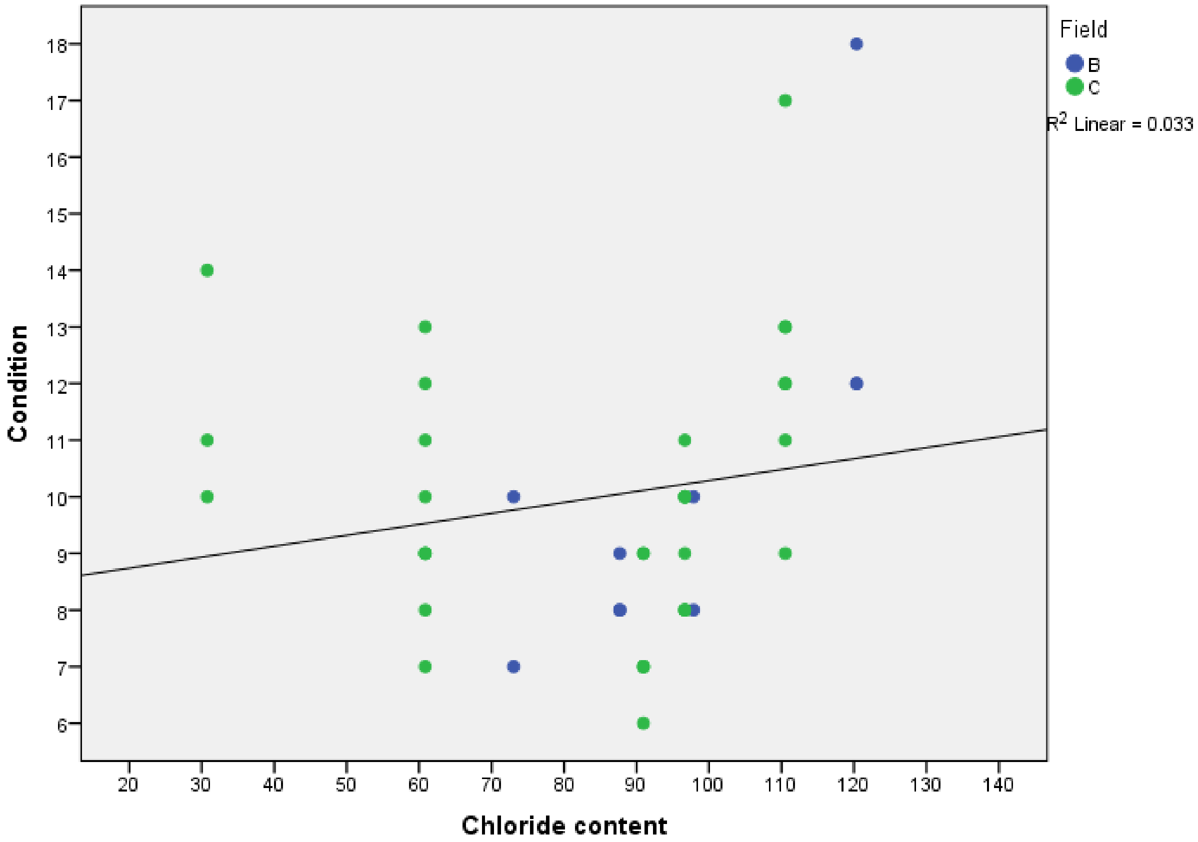


Figure 124: Scatter plot showing the chloride content (mg/kg) of soil against the condition of bullets, showing slight positive correlation, but not at a statistically significant level.

			Condition	Chloride
Spearman's rho	Condition	Correlation Coefficient	1.000	.291
		Sig. (2-tailed)	.	.055
		N	143	44
	Chloride	Correlation Coefficient	.291	1.000
		Sig. (2-tailed)	.055	.
		N	44	44

Table 44: Spearman's rank correlation coefficient of 0.291 for the relationship between chloride content of soil and bullet condition, which is not significant.

5.7.8 Statistical overview

Statistical analysis of each soil parameter against the condition of lead bullets from the site of Moreton Corbet has revealed very few significant correlations. More definitive information may be available once all three case studies are combined and compared as a whole data set as this would provide a greater number of samples (see chapter 8).

Even though no soil parameter has been found to be significant in terms of their correlation with the condition of the bullets from the site of Moreton Corbet, there have been suggestions throughout the assessment of the data that particular areas of the site may exhibit characteristics that correspond with the condition of bullets. Spatial analysis of each field in turn may identify patterns which did not emerge during statistical analysis. As set out in the introduction and aims of this project, an area that needs consideration is the spatial mapping of artefact condition across sites in order to identify any trends in deterioration or preservation. As 78% of the artefactual evidence resides in Field C, this field forms the main area of analysis, though fields A and B are also assessed in terms of their topography, historic land use and soil attributes.

5.8 Spatial analysis

5.8.1 Field A

Only 17 bullets were retrieved from Field A, 10% of the total collection. The northern end of the field had not been detected at the time of analysis and as a result only the southern end has been studied in this research. 53% of the bullets from Field A scored a 3 of fair overall condition with only one score of very good and one score of poor. This field is fairly flat (figure 125) and lateral movement of bullets will have been minimal due to the lack of sloping ground (Haselgrove 2007, 8).

As discussed in section 5.4, this field was marked as an area of 'moor' in the 18th century. The field boundaries have not changed since the 1838 tithe map and appear to have been in constant use as grassland/pasture up until the 1990s when it was used for cereal crops. Considering the relatively small scale of cultivation in this field it might be expected for the bullets to be in slightly better condition, as they are in the track way of Field B (see section 5.8.2.1). Seven bullets also show signs of abraded surfaces, suggesting attrition and movement in the soil has occurred (table 45).

Soil analysis in this field is restricted as only two test pits were dug. pH of the topsoil is slightly acidic, ranging from 5.85 to 6.03, but deeper deposits are neutral at 7.01-7.03 pH. Conductivity is low to moderate, from 88.57 to 187.23µS/cm. Water content is also moderate, ranging from 17.77 to 20.55% and organic content is fairly low, from 5.89 to 6.25%. Test pit 6 to the western end is a clay loam as opposed to test pit 7 at the eastern end of the field which is a sandy loam.

As discussed above (section 5.7.1), the pH readings from Field A are just in a 'safe' zone for lead preservation; anything below 5.5 may start to affect the deterioration of lead. However, the pH levels in Field A are some of the lowest at the site, suggesting that some areas of the field may be acidic enough to disrupt the stability of the lead bullets. No other soil attribute recorded in this field appears to be aggressive enough to trigger lead decay.

However, due to limited sampling and low number of bullets retrieved, there is not enough data available from this field to draw any firm conclusions on the condition of the bullets. However, it is surprising that condition is not better in a field that has remained predominantly in pasture use for the last two centuries. The answer may lie in the land use of the field prior to the 18th century. A further in depth study of medieval land use would be required to investigate this, but is beyond the scope of this study.

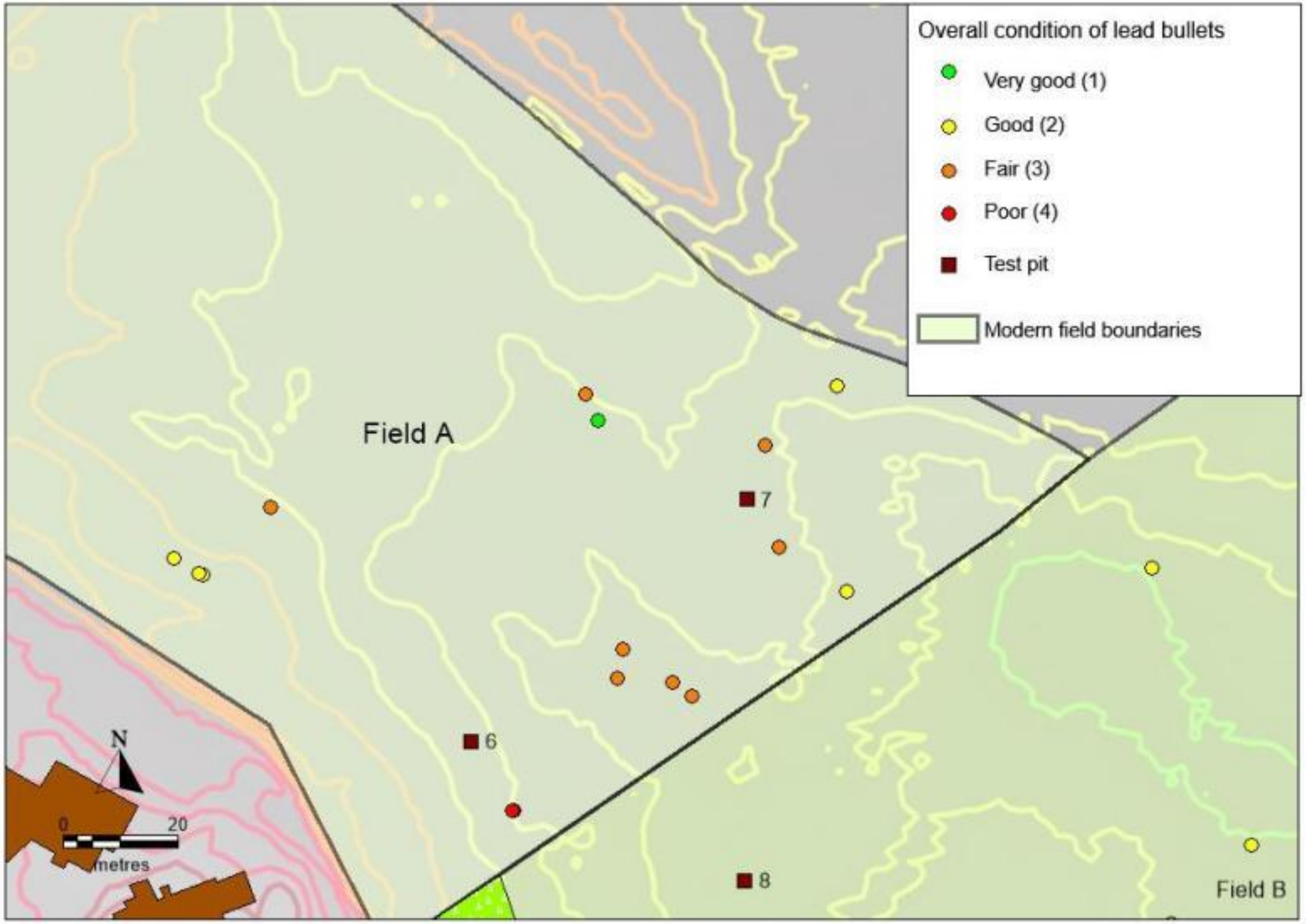


Figure 125: Field A showing the distribution of lead bullets and their overall condition. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

Attribute	Number of bullets scoring condition 1 (very good)	Number of bullets scoring condition 2 (good)	Number of bullets scoring condition 3 (fair)	Number of bullets scoring condition 4 (poor)
Overall condition	1	6	9	1
Smoothness of surface	0	9	5	3
Preservation of shape	14	3	0	0
Surface detail	3	10	3	1
Corrosion products	4	11	2	0
Stability of surface	1	5	9	2
Localised corrosion	7			
General corrosion/pitting	2			
Hit by plough	0			
Abraded surface	8			
Cracks	2			

Table 45: The condition attributes assigned to lead bullets from Field A.

5.8.2 Field B

Field B can be split into two zones based on land use history; the eastern end which has been grassland until the early 1980s when it was brought into cultivation, and the thin strip to the west alongside the castle, termed the 'track way', which was grassland up until 2014 and has only been ploughed once before the retrieval of artefacts from the field (figure 126). Eight test pits were dug in Field B. The location of samples was based on topographical features in the landscape, as well as the recorded overall condition of bullets.

5.8.2.1 Track way

The track way used to form a part of 'Castle meadow' in the 18th century and sits directly to the east of the castle structure (figure 126). It also resides in an upslope area of the site just before the land drops down to the east where a linear terrace resides mid slope. Throughout the 19th and 20th centuries the track way forms a part of the grasslands surrounding the castle. By the early 1980s the rest of Field B has been converted to arable cultivation, but this strip of land was retained as grassland for access to the south west corner of Field A. It is only in 2014 that this strip of grass was ploughed and incorporated into the arable field.

The five bullets retrieved from the former track way were all recorded as very good or good overall condition. They consistently scored a 1 or 2 in all five condition categories, except one which scored a 3 for fair surface detail preservation (table 46). None of the bullets from this section of the field had suffered severe abrasion, pitting, or had any indication of being hit by machinery in the ground. Two did however, show signs of surface cracking, which could be a result or stress corrosion cracking or as a result of the lead drying out upon excavation (figure 127).

Abrasion to the surface of bullets is quite a prevalent issue on this site, with 61 bullets in total showing signs of severely abraded surfaces. The fact that no bullets from the track way showed signs of abrasion and all had solid smooth patinas (figure 128) is likely to be due to the lack of ploughing in this part of the field in recent history. As stated by Edwards (1996), stress corrosion cracking and subsequent localised corrosion is often triggered when the patina is broken or weakened, through acts of abrasion or compaction in the ground. The lack of any significant corrosion in this area is highly likely to be down to lack of soil cultivation.

The former track way resides on the top of a slope, between 67-69m AOD, and a lack of cultivation has restricted the bullets moving down slope through displacement. The fact that the area has only recently been put under the plough suggests that bullets reside lower down in the topsoil than in other areas of the site. Lack of ploughing will have allowed the bullets to sink vertically in the ground near to the base of the ploughsoil, thereby aiding their preservation. This is also likely to have resulted in the small number of bullets retrieved from this area during surveys as some bullets may not yet have been brought nearer the surface in the range of metal detectors (Canti 2003; Foard 1995, 20).

pH of topsoil in the track way ranges from 5.49 to 6.36, averaging at 5.84±0.39 which is more acidic than the average topsoil across the site of 6.05±0.43. pH 5.49 is the most acidic reading from the whole site, indicating this area is relatively acidic. This acidic tendency in the track way continues through the soil column. As discussed in section 5.7.1, this region of acidity is just in a 'safe' range for the survival of lead in soils. Any lower than pH 5.5 would begin to seriously affect their preservation. This is one of the most acidic areas on the site and it is likely that pH levels fluctuate throughout the year. Levels of acidity have not compromised the condition of bullets in the track way, though in other areas of the site bullets are in poor condition with a similar level of acidity (see section 5.8.3). This suggests that another factor has overarched the impact of acidity on the preservation of bullets in this zone.

The conductivity of the track way is relatively low, with all topsoil samples bar one sample reading below 100µS/cm. However, test pit 4 had a conductivity of 300.33µS/cm which is relatively high; double the site average. Water content across the track way varies quite considerably, ranging from 14.8% to 23.8% over a distance of 90m. Topographically the test pits are at similar heights of 67.50-68.50m AOD. Water content is particularly high in the topsoil from test pit 4 which also had the highest conductivity levels. This test pit is also the most acidic and has the highest organic content in the track way of 9.41%; the next highest reading from the topsoil being 5.86%. Test pit 4 is also the only topsoil sample to be a sandy clay loam, whereas the rest of the topsoil samples in this region are loamy sands or sandy loams (figure 129). It is likely that the higher clay content from this test pit accounts for higher water, organic and conductivity levels.

Overall, the track way has relatively low levels of water, organics and conductivity, but is slightly acidic, though the level of acidity has not impacted on the condition of the bullets. It appears that the most significant attribute in the track way is the lack of corrosion and abrasion damage on lead bullets through a lack of cultivation. Further detecting in this area in future years after several more episodes of ploughing may bring more bullets in metal detecting range and more data could be gathered to develop the theory that a lack of cultivation is the overarching factor preserving the lead bullets.

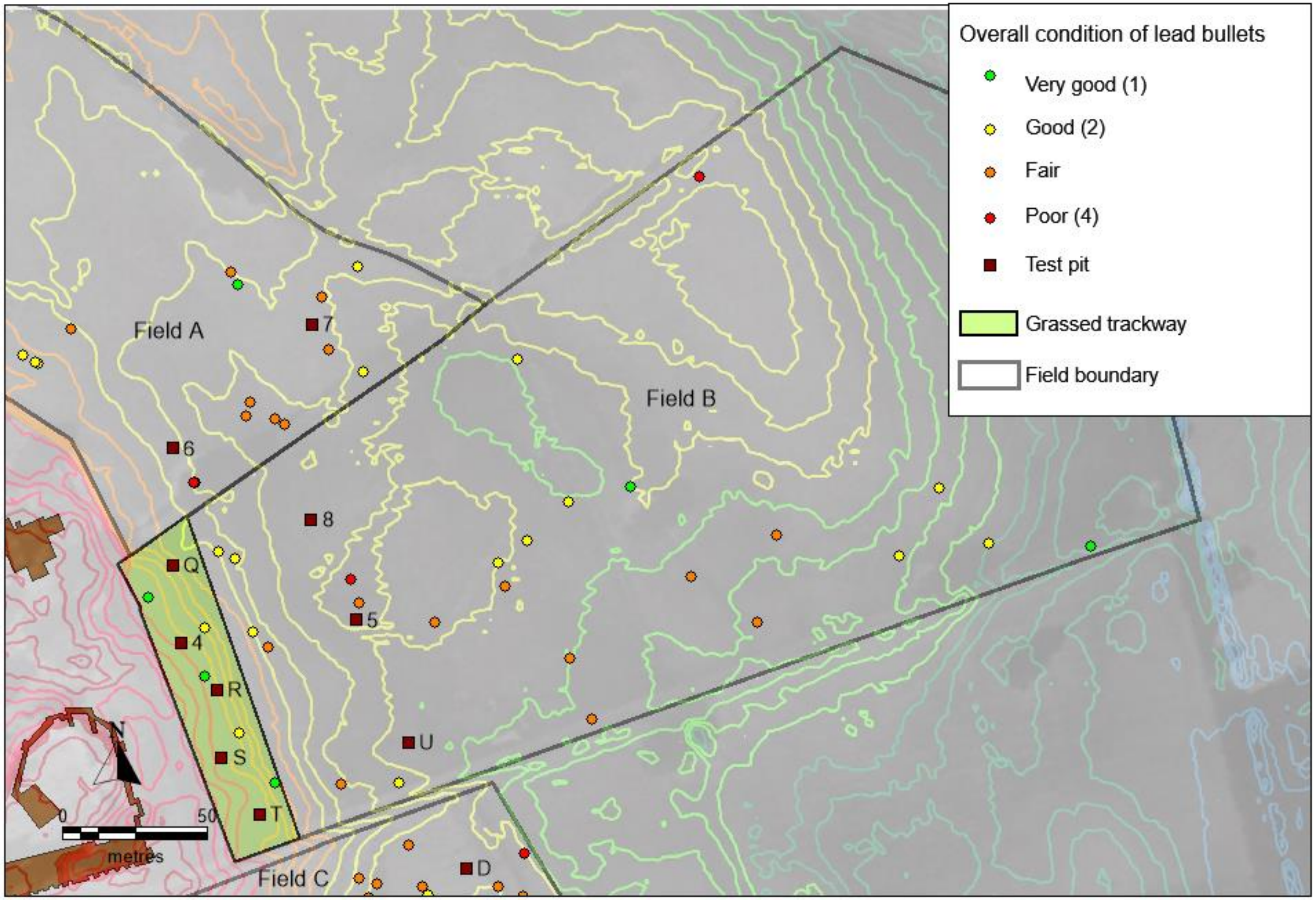


Figure 126: Field B showing the overall condition of lead bullets. All bullets in the highlighted track way scored a 1 (very good) or 2 (good) for condition indicating a good level of preservation. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

Attribute	**Number of bullets scoring condition 1 (very good)**	**Number of bullets scoring condition 2 (good)**	**Number of bullets scoring condition 3 (fair)**	**Number of bullets scoring condition 4 (poor)**
Overall condition	3	2	0	0
Smoothness of surface	2	3	0	0
Preservation of shape	2	3	0	0
Surface detail	4	0	1	0
Corrosion products	1	4	0	0
Stability of surface	2	3	0	0
Localised corrosion	1			
General corrosion/pitting	0			
Hit by plough	0			
Abraded surface	0			
Cracks	2			

Table 46: Number of bullets from track way in Field B and associated condition scores.

Figure 127: Evidence of surface cracks on lead bullet found in track way (MOR 0014).

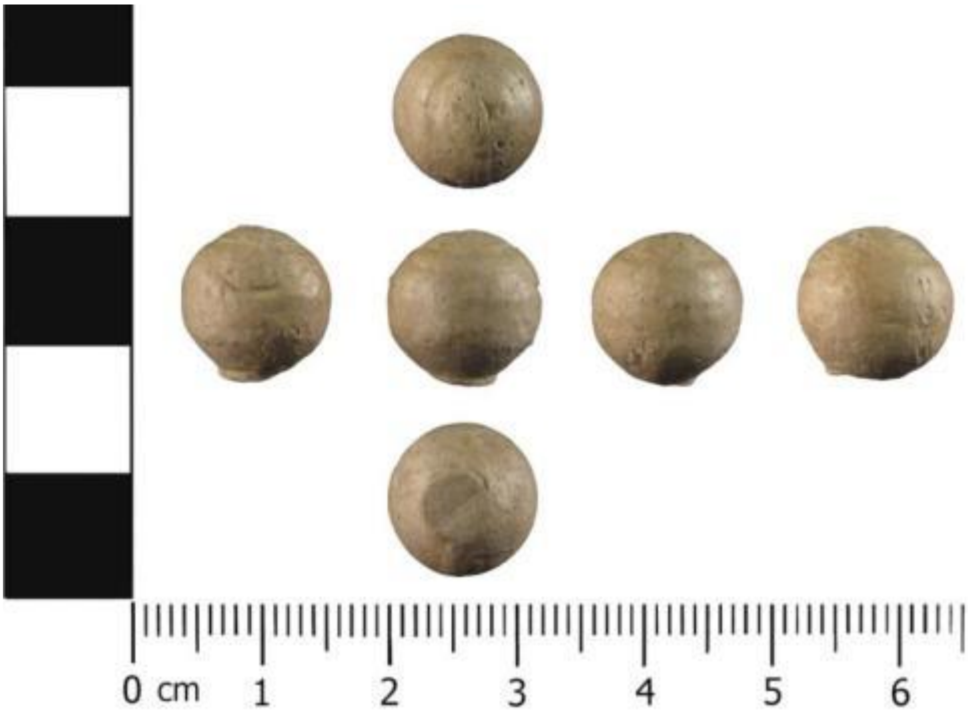


Figure 128: Example of lead bullet from track way with clean smooth patina and little signs of damage

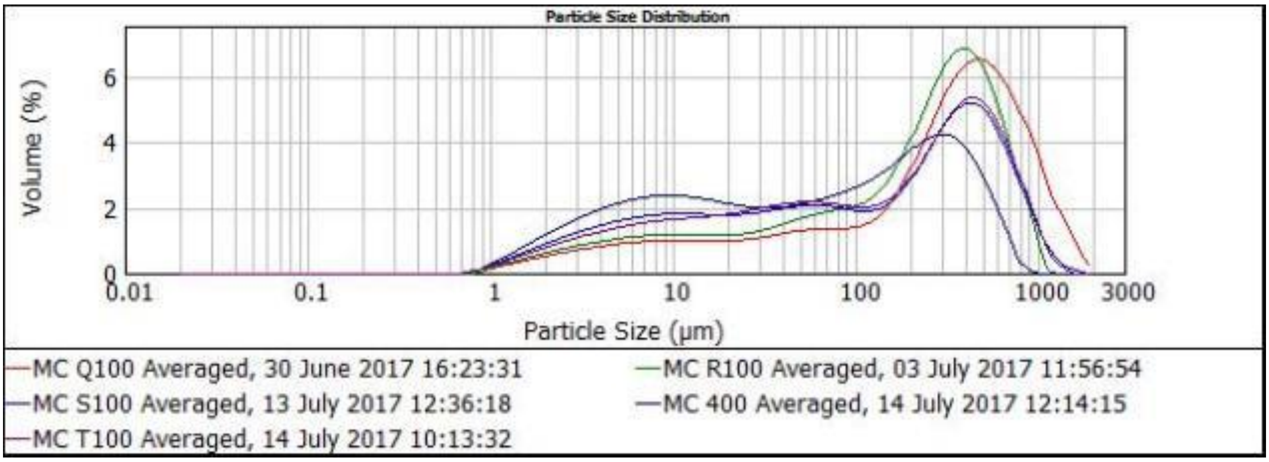


Figure 129: Results of texture analysis for topsoil samples from the track way showing a tendency towards a high sand content. Each curve represents a separate test pit from the track way.

5.8.2.2 East part of Field B

Field B comprised three separate fields in the 18th century, forming a part of the 'Castle meadow', 'Swines wood' and 'Pond meadow' (section 5.4.1). By the 1st edition Ordnance Survey (Ordnance Survey of England and Wales 1884), Field B was one large field comprising the northern portion of what is now Field C. Several field boundaries were replaced in the 20th century and it was not until the early 1980s that the road separating fields B and C was constructed and the current field boundaries were established. It was also around this time that Field B was taken out of pasture use and converted to arable and pig farming.

Three test pits were dug in Field B in a line running NW to SE following topographical features identified in field observations (figure 130). During fieldwork a waterlogged area in the field was identified where the site drops to a height of 66m AOD (figure 131). The landowner confirmed this area of the field frequently becomes waterlogged after consistent rainfall (Pinches Pers. Comm.. 08.12.2014). Linear features were also noted in the field in the form of dark crop marks (figure 132), which correspond with the 1983 aerial photograph and follow drainage channels across the site (Cartographical Services Ltd 1983).

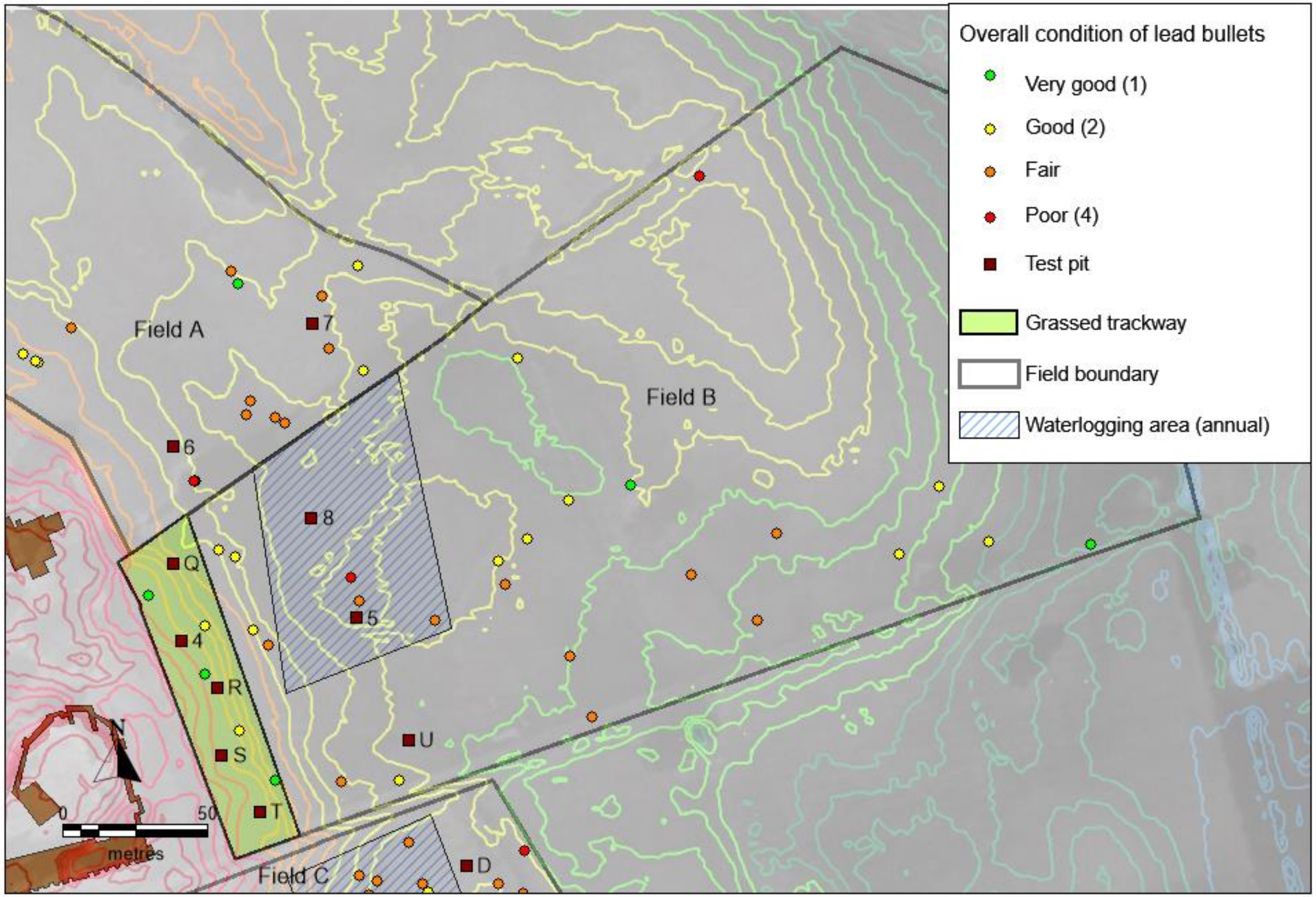


Figure 130: Field B showing the overall condition of lead bullets. Areas which become waterlogged annually are also highlighted. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

Figure 131: Slight waterlogging in spring 2016 in Field B near to test pit 8.

Figure 132: Looking north east across Field B revealing a dark soil mark where the field dips.

The condition of bullets across Field B is quite varied, with 21 out of the total 25 bullets scoring a 2 for good or 3 for fair overall condition. Scoring of the five condition categories varies quite significantly across the site, though few bullets score 1 or 4 in any category (table 47).

Bullets in better condition cluster towards the eastern end of the field or directly adjacent to the edge of the former track way. Their vicinity to the base of the slope may indicate their gradual movement down slope and their subsequent deterioration (figure 133). As others have observed, most artefact displacement occurs downhill or in the direction of ploughing (Roper 1976, 373).

Bullets in worst condition are found in the area at the bottom of the sharp slope where the land begins to level out, sitting in annually waterlogged zones of the field. This area of the field has also been under constant cultivation since the early 1980s. The far eastern end of the field has often been in use for pig farming and has been cultivated less, as has the track way to the west. The most topographically significant feature in this field appears to be the steep slope which corresponds with bullets in good condition at the top of the slope, and bullets in poor condition at the bottom of the slope.

Bullets with localised corrosion or abraded surfaces are common in this field (figure 133). However, only four bullets had severe evidence for both abrasion and localised corrosion and both attributes are dispersed across the whole field with no distinct patterns. It is difficult to establish when and how the bullets developed these corrosion issues, but as the field has been cultivated regularly since the 1980s the bullets are likely to have been laterally displaced and abrasion is likely to be a result of ploughing the predominantly sandy soil. Abrasion is likely to have an impact on the condition of bullets as their preservation is ultimately determined by the stability of their surface patina. Ploughing sandy soils allows large abrasive sand particles to come in to contact with the surface of bullets, which will gradually wear down their surface and allow localised corrosion to develop (Edwards 1996, 91).

Attribute	Number of bullets scoring condition 1 ((very good)	Number of bullets scoring condition 2 (good)	Number of bullets scoring condition 3 (fair)	Number of bullets scoring condition 4 (poor)
Overall condition	2	11	10	2
Smoothness of surface	0	15	8	2
Preservation of shape	19	5	1	0
Surface detail	8	7	8	2
Corrosion products	9	11	4	1
Stability of surface	1	14	7	3
Localised corrosion	13			
General corrosion/pitting	2			
Hit by plough	0			
Abraded surface	10			
Cracks	1			

Table 47: Number of bullets from east part of Field B and associated condition scores.

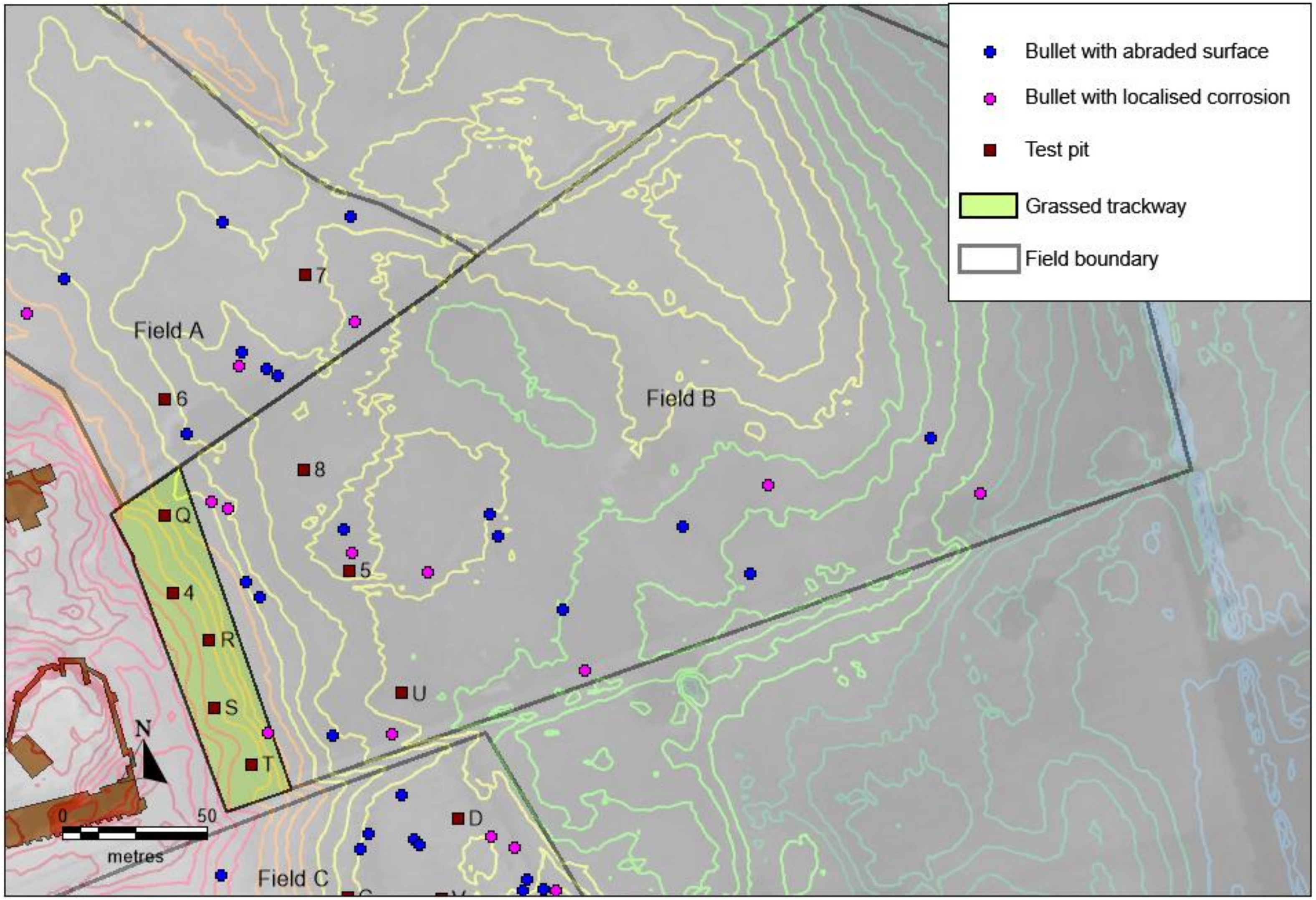


Figure 133: Field B showing the distribution of abraded bullets and bullets with localised corrosion. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

pH of the topsoil in the east part of Field B is neutral to slightly alkaline, ranging from 6.24 to 7.29, which is higher than levels observed in the track way. These levels are not predicted to be damaging to the preservation of lead. Conductivity varied considerably across the 90m area of investigation, from 77.9μS/cm to 425.33μS/cm. Water content also varied quite considerably, with fairly high levels ranging from 16.81% to 21.1%. Organic content was fairly low, averaging at 5.42±0.67%. All three test pits were consistently sandy soils throughout the soil column with no trace of significant clay contents, which is confirmed by the Geological Survey map (Ordnance Survey of Great Britain 1967). The waterlogging in this area of the site indicates that the water table was relatively high at the time of sampling. During fieldwork, it was observed that test pits 5 and U began to fill up with water once a depth of 0.60m was reached. This was not observed in upslope areas of the site. The waterlogging issue in Field B is reiterated by the placement of drainage channels in the down slope area of the field in the 20th century.

It appears that the high sand content in this region of the site has allowed bullets to degrade as they are moved by a means of cultivation and abrade against large sand particles. Down slope areas may be vulnerable to fluctuating water tables which may also account for the deterioration in preservation in lower areas of the field. It is worth undertaking further experimental work into the effects of abrasion and attrition of bullets in sandy deposits in order to assess this issue in more detail.

5.8.2.3 Overview of Field B

Though few bullets scored very good or poor in the condition categories, it is clear that preservation is best to the western upslope end of Field B in the former grassed track way. In terms of soil conditions, the track way is slightly more acidic, has lower conductivity, lower water content, lower chloride content and slightly higher organic content (table 48).

It appears the overarching factors influencing the condition of bullets in Field B are the land use and topography. Bullets in the track way which has only just come under cultivation are very well preserved and show no signs of abrasion. Bullets to the east, down slope where the land has been cultivated almost constantly since the early 1980s, are in much poorer condition. It is likely that a combination of cultivation in sandy well drained soils has accelerated the corrosion of the bullets. Ploughing will have mobilised the bullets in the soil, allowing a greater flow of oxygen and water which will accelerate the corrosion process. As bullets are churned in sandy soils, the risk of abrasion increases which will break down the protective patina layers on the bullet surface. As a result, the bullets will be more prone to developing localised corrosion and their condition will deteriorate. Bullets down slope may also be vulnerable to fluctuating water levels, as witnessed in field observations. Fluctuations in water tables have been shown to have a damaging impact on the preservation of metals (Graham and Williams 2008). Nonetheless, cultivation appears to be the triggering factor which develops the process of deterioration.

Soil attribute	Average soil attributes of topsoil in track way	Average soil attributes of topsoil in east part of field
pH	5.84	6.72
Conductivity	125.8µS/cm	203.4µS/cm
Water content	18.24%	19.49%
Organic content	6.25%	5.42%
Texture	Sandy loams and clay loam	Sandy loams
Compaction	loose	Very loose
Nitrate content	119.9mg.kg	109mg/kg
Chloride content	80.36mg/kg	109.11mg/kg

Table 48: Comparison of soil conditions between the two zones of Field B.

5.8.3 Field C

Field C has by far the most archaeological data available from the site, with 78% of the bullet assemblage retrieved from this field (figure 134). The largest numbers of bullets score a 2 for good overall condition and there is an overall trend for bullets to score 2s or 3s in the condition categories (table 49).

Abraded bullets are common in this field, with 70% of the abraded bullets from the site retrieved from Field C. Though abrasion is common across the whole field, there is a tendency to find abraded bullets on the edge of the slope or down slope to the middle and eastern end of the field; none are found with abraded surfaces above 68.75m AOD to the western end of the field which forms the former formal garden plateau (figure 135). The lack of abrasion in the flat area to the west may be to do with soil depths. Bullets in the formal garden area may have been buried by garden soil and therefore been protected from constant abrasion in the soil induced by ploughing episodes. More abrasion occurs at the base of the slope and across the lower portion of the field in annually waterlogged areas. This pattern was also present in Field B, with no abrasion upslope in the former track way.

Lateral displacement of bullets is much more likely down slope than over flat land and some of these bullets may have been displaced down slope through ploughing episodes and been abraded in the process (Haselgrove 2007, 8; Darvill and Fulton 1998, 177). Normally over flat areas objects only move a distance of around 2 metres from their original location, though this can increase drastically down slope (Ammerman 1985, 38). In the case of Field C, clusters of bullets reside at the top and base of the terrace, but not in the slope itself, suggesting that movement of bullets has occurred swiftly between the top and bottom of the scarp. This rapid movement downhill will have increased the likelihood of abrasive damage.

There is a distinct pattern of areas of very good and poor preservation in Field C. If all bullets which scored a 1 or 4 for overall condition, smoothness of surface, surface details and stability of surface are mapped, it becomes apparent how prevalent good preservation is upslope to the west, whereas there is a cluster of bullets in poor preservation lying along the base of the slope (figure 136). As in Field C, this pattern of poor preservation follows the line at the base of the scarp where the site is prone to waterlogging, also prevalent on the 1983 aerial photograph as a dark soil mark (RAF CPE/UK 201, 3351, RAF/58/5171 291, Shropshire archive Cartographic service no. 1099). This pattern also emphasises the presence of bullets in poor condition sitting against the base of the slope, suggesting they may have been displaced downhill from the formal garden plateau to the west.

Three zones were identified across Field C based on bullet condition and topography: zone A covers the western upslope corner of the former formal gardens; zone B covers the base of the slope in the centre of the field; zone C covers a small area to the eastern edge of the field (figure 137). The mid slope was left out of discussion due to significantly fewer bullets being recorded from this area.

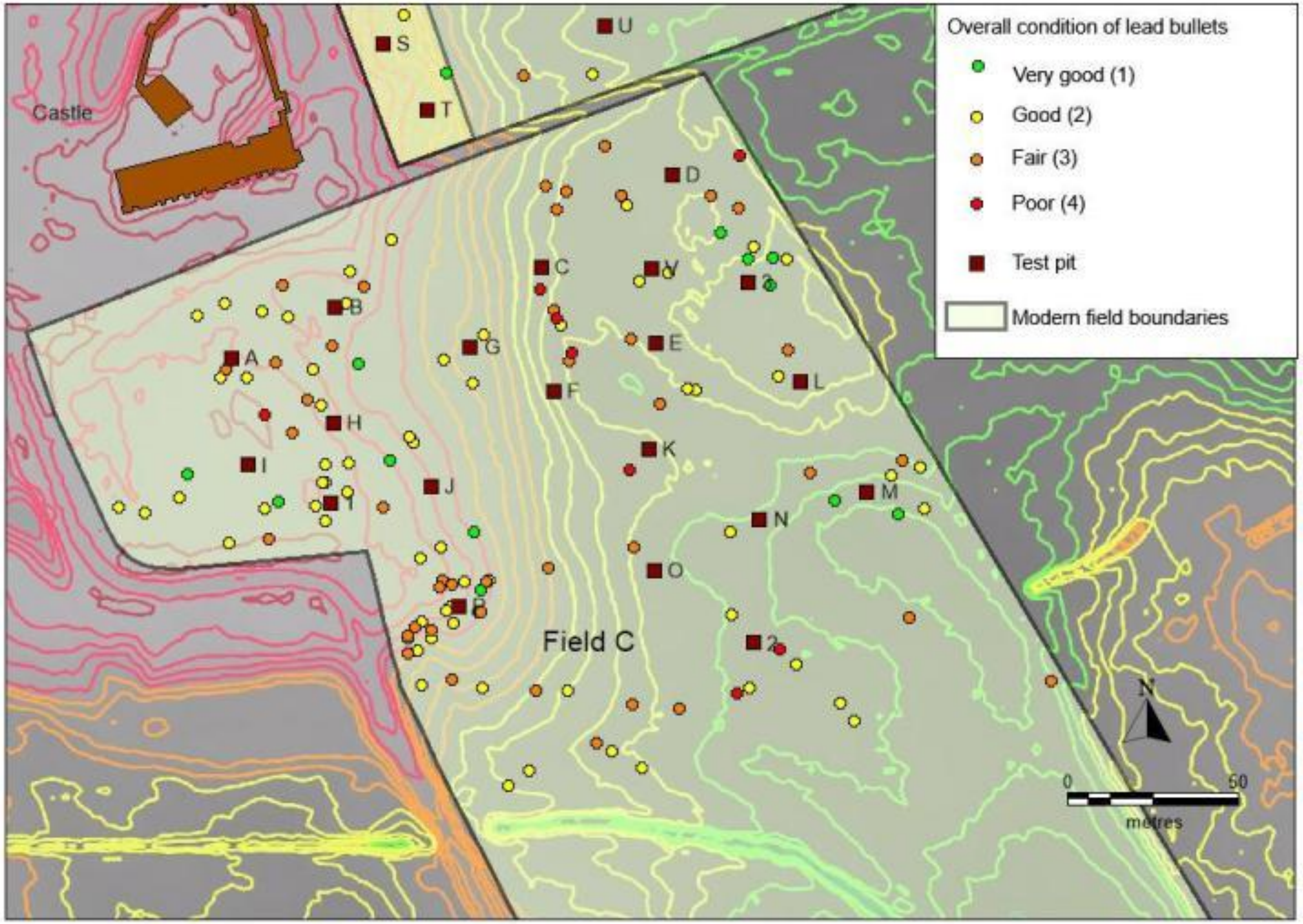


Figure 134: Field C mapping the condition of lead bullets and the location of test pits (test pits are labelled 1-8 and A-V). Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

Attribute	Number of bullets scoring condition 1 (very good)	Number of bullets scoring condition 2 (good)	Number of bullets scoring condition 3 (fair)	Number of bullets scoring condition 4 (poor)
Overall condition	13	66	43	8
Smoothness of surface	15	73	35	7
Preservation of shape	83	44	2	1
Surface detail	29	69	24	8
Corrosion products	46	56	24	4
Stability of surface	18	69	39	4
Localised corrosion	39			
General corrosion/pitting	8			
Hit by plough	5			
Abraded surface	43			
Cracks	8			

Table 49: Condition attributes and associated condition scores for bullet from Field C.

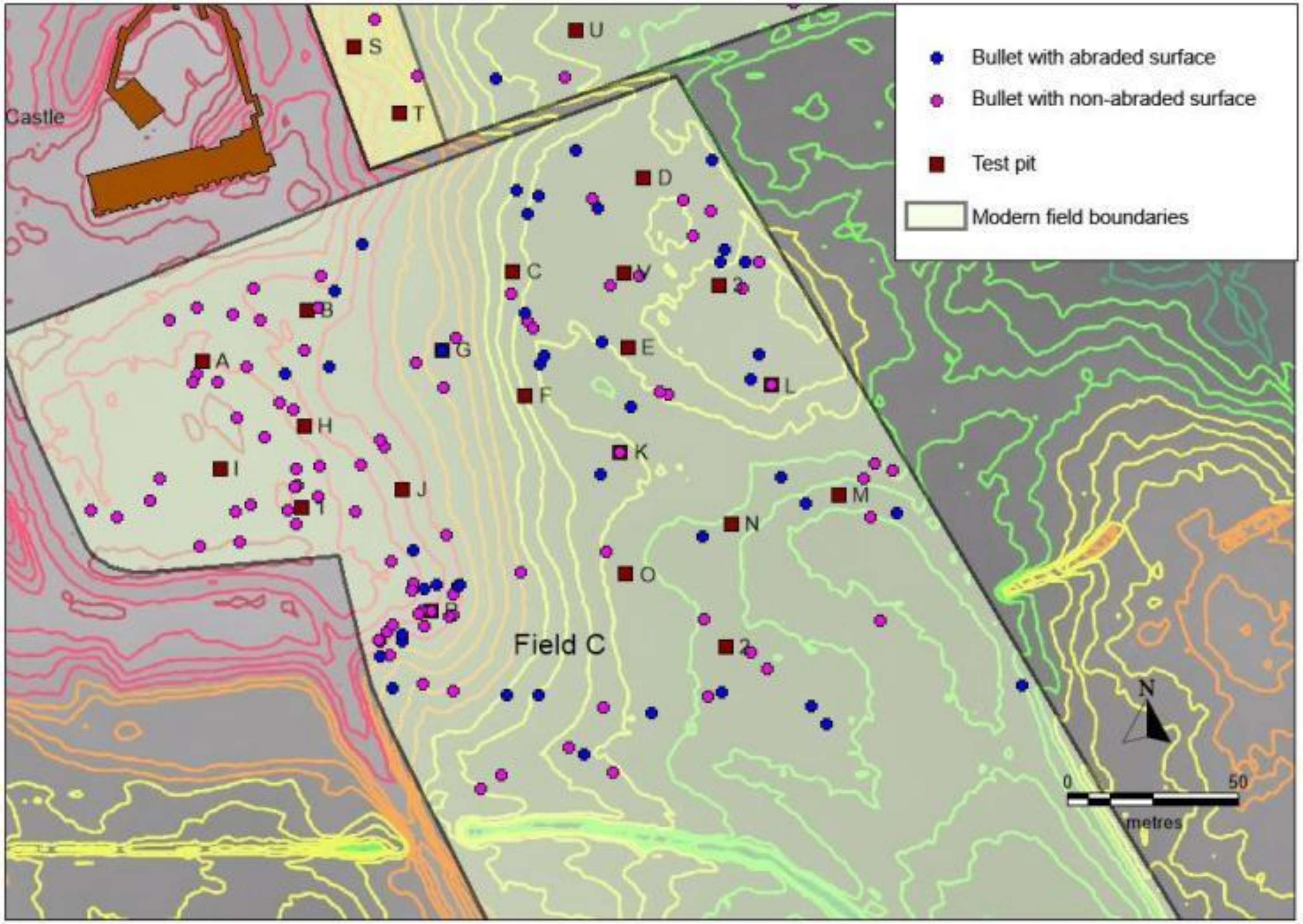


Figure 135: Map of abraded and non-abraded bullets retrieved from Field C, indicating a lack of abraded bullets in upslope areas to the west. There is a distinct lack of bullets present within the slope suggesting rapid downhill displacement. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

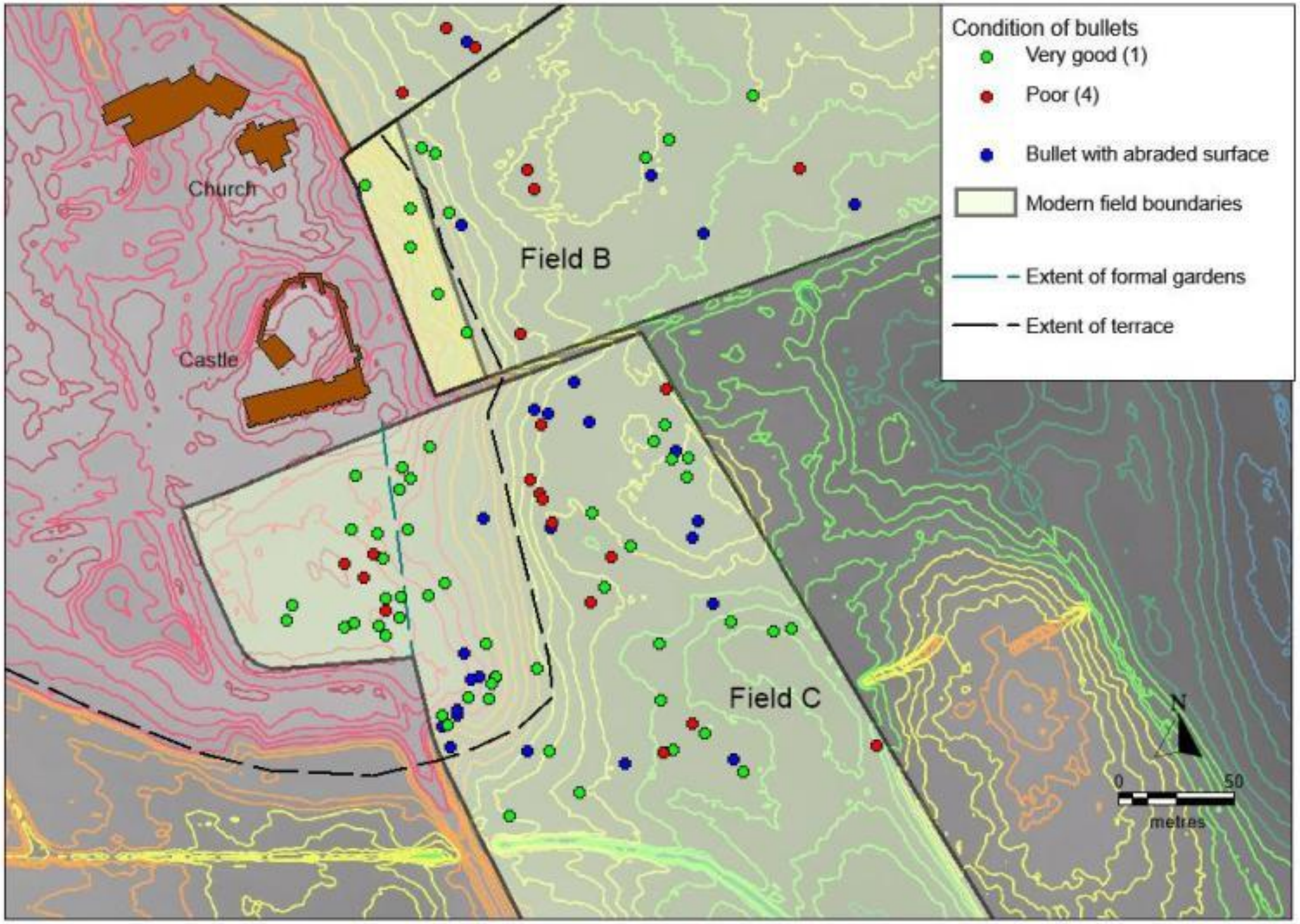


Figure 136: Condition of bullets including abraded bullets from Field C. Distinct areas of good preservation lie upslope in the former formal gardens and upslope of the terrace. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

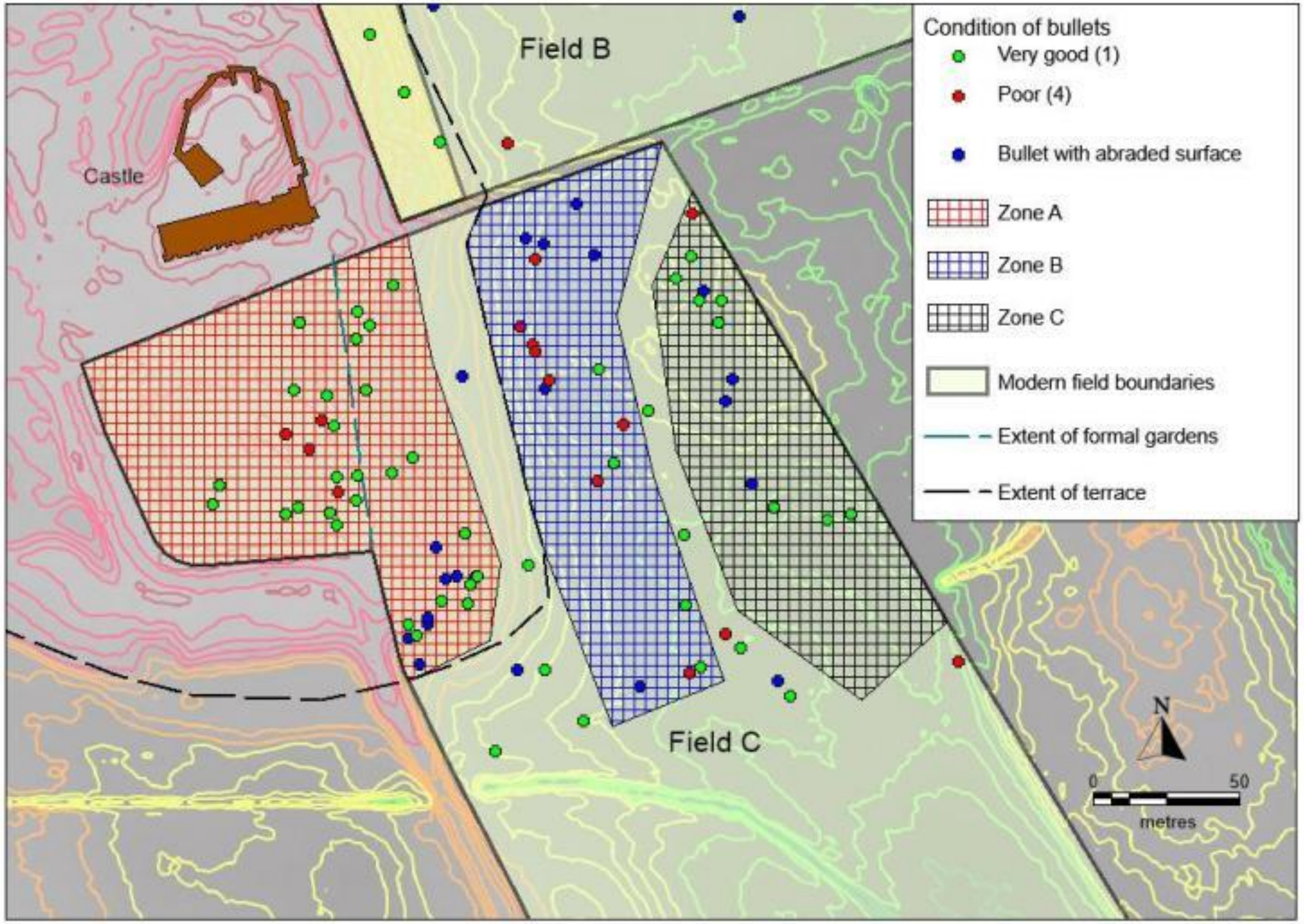


Figure 137: Designated zones in Field C for discussion, based on topography, slope, land features and bullet condition. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

5.8.3.1 Zone A

The pH of topsoil samples from zone A range from 5.54 to 6.31, with an average of 5.87 ±0.30, indicating a slight acidic tendency. Conductivity levels are between 87.83μS/cm to 215.1μS/cm. Water content varies little, from 10.37% to 12.46% in topsoil, and organic content ranges from 5.01% to 6.96%. Texture in this zone is predominantly sandy loams throughout the soil column. Nitrate content of the topsoil varies considerably, from 142.5mg/kg to 702.7mg.kg. Chloride content ranges from 60.84 to 96.66mg/kg.

The pH is slightly acidic in this region of the site, with topsoil averaging slightly lower than the site average of 6.05±0.43. This slight acidity continues through the soil column. Conductivity levels are slightly lower than the site average of 154.6μS/cm, which could be due to the fairly low water content in this region with its average content of 11.55±0.82%, much lower than the average topsoil content across the site of 15.9±0.03%. Nitrate content was measured in two test pits and differed dramatically. 702.7mg/kg is particularly high compared to the topsoil average of 243.2mg/kg. The chloride content average of zone A was 78.75±25.33mg/kg which is similar to the site topsoil average of 85.41mg/kg.

Statistical analysis was carried out between the individual soil parameters and the condition of bullets from Zone A in Field C, but did not provide any statistically significant results (see section 5.7). There was a very slight relationship between the condition of bullets in this zone and the texture of the soil. As the graph shows (figure 138), there is a very slight trend for the condition to improve as clay content increases. However, the coefficient value for this relationship is -0.167 which is not very strong (table 50). There is also a very slight trend for condition score to increase and therefore condition worsen as sand content increase (figure 139). Again however, this relationship is not strong and has a coefficient of 0.167 which is not significant (table 51).

This zone has particularly good preservation of bullets, regardless of the slight acidic tendency of the soil. The low water content and fairly low conductivity levels will aid in reducing the rate of corrosion. There is a small cluster of abraded bullets to the south end of zone A where the land begins to slope downwards. This is perhaps an indication that these bullets are beginning to be displaced down slope.

The upslope and fairly dry nature of this zone is likely to have helped preservation of the artefacts. This area predominantly resides in the former area of formal gardens and contains no abraded bullets. This flat garden area is likely to have reduced artefact displacement whilst also providing a garden soil layer which is likely to have raised the soil level, protecting bullets from direct plough damage, movement and attrition in the ground.

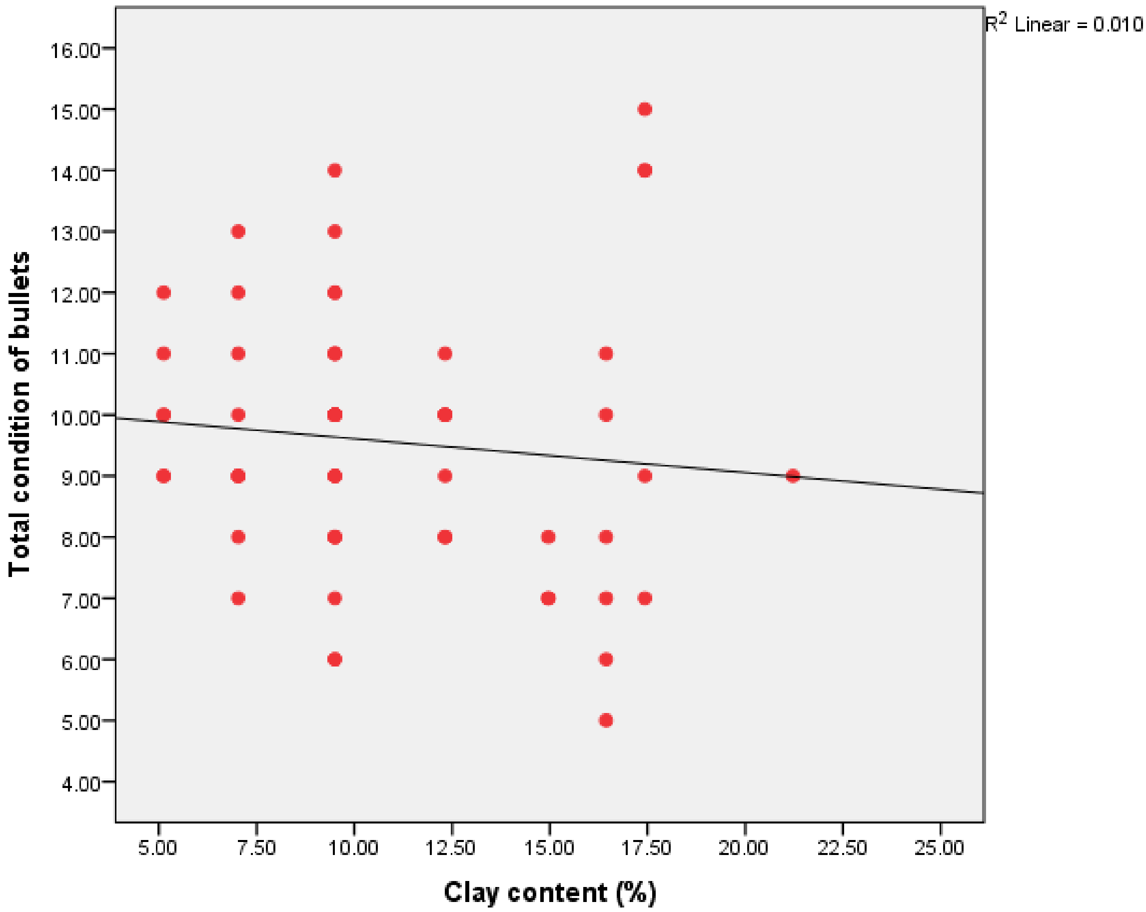


Figure 138: Scatter plot showing the relationship between the soil clay content and condition of bullets in Zone A of Field C. As clay content increases, bullet condition improves. However, the relationship is slight and not statistically significant.

			Condition	Clay
Spearman's rho	Condition	Correlation Coefficient	1.000	-.167
		Sig. (2-tailed)	.	.188
		N	64	64
	Clay	Correlation Coefficient	-.167	1.000
		Sig. (2-tailed)	.188	.
		N	64	64

Table 50: Spearman's rank correlation coefficient of -0.167 for the relationship between clay content and the condition of bullets, indicating a very slight negative correlation that is not statistically significant.

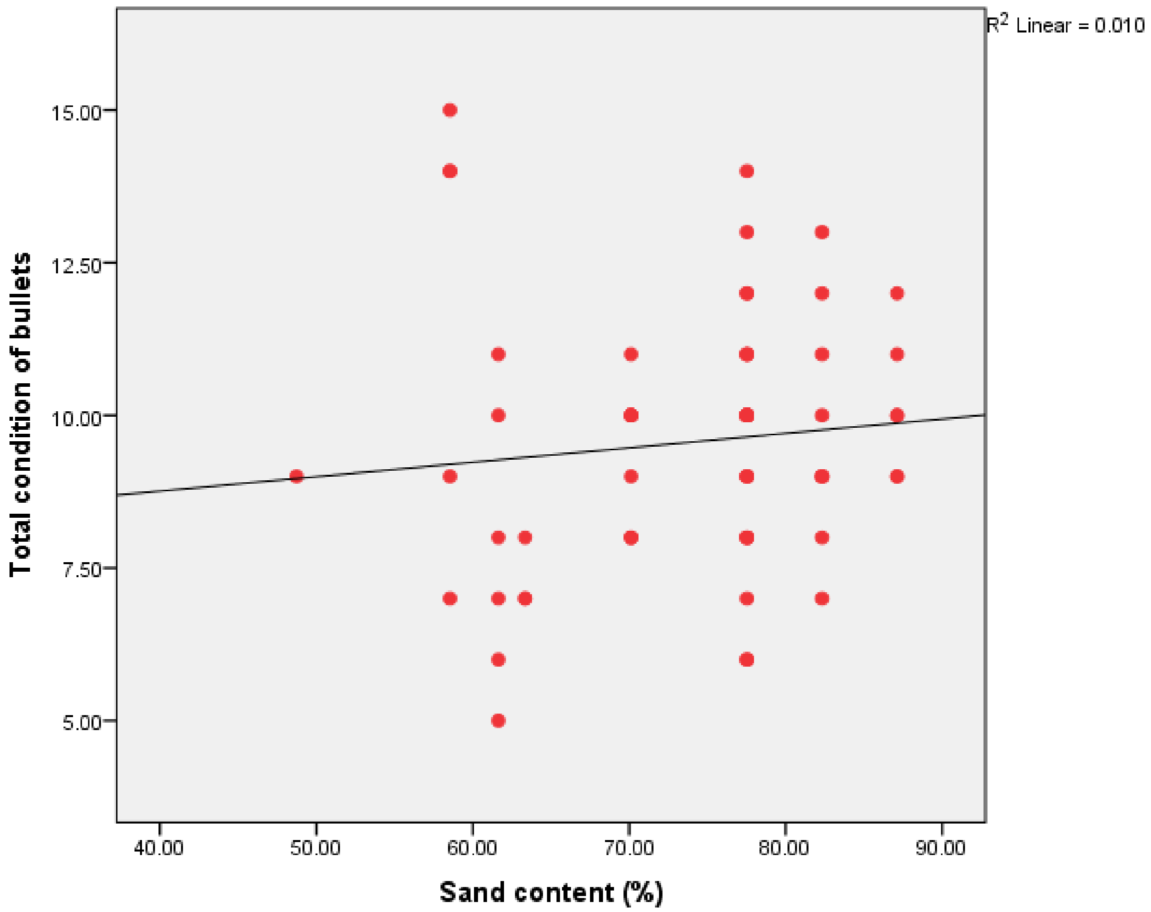


Figure 139: Scatter plot of the relationship between sand content and the condition of bullets in zone A of Field C showing a very slight positive correlation with condition score increasing with increasing sand content.

			Condition	Sand
Spearman's rho	Condition	Correlation Coefficient	1.000	.167
		Sig. (2-tailed)	.	.188
		N	64	64
	Sand	Correlation Coefficient	.167	1.000
		Sig. (2-tailed)	.188	.
		N	64	64

Table 51: Spearman's rank correlation coefficient of 0.167 for the relationship between sand content and the condition of bullets which is not statistically significant.

5.8.3.2 Zone B

pH of topsoil in zone B ranges from 5.65 to 6.7, with an average of 6.27±0.37. Lower deposits reach highest levels of 7.04. Conductivity levels in topsoil ranges from 80.6μS/cm to 263.67μS/cm. Water content ranges from 13.98% to 19.58%, and organic content ranges from 5.33% to 7.96%. Four topsoil samples were recorded as sandy loam and four as clay loam, with all but one subsoil sample recorded as clay loam. Nitrate content was recorded in two samples at 116.6mg/kg and 503.8mg/kg. Chloride content was recorded at 30.75mg/kg and 110.52mg/kg.

The pH of soil in zone B is slightly acidic to neutral. Conductivity levels are slightly higher than the site average, as is water content. Organic content average is slightly higher than the topsoil average across the site, though organic content is not particularly high in any part of the site. The nitrate content average of 310.2±272.80mg/kg is higher than the average across the site of 243.2mg/kg, and chloride content average of 70.64±56.41mg/kg is slightly lower than the site average of 85.41mg/kg.

This area of the site lies at the base of the slope in the centre of the field and corresponds with the former road from the airbase running through the middle of the field. It is likely that the topography, the higher water content, annual waterlogging, clay content, as well as the abrasive effects of ploughing has caused damage to bullets in this area. Though zone A contains 13 abraded bullets and zone B contains 14 abraded bullets, 9 of zone A's 13 sit on the edge of the slope, perhaps suggesting displacement due to ploughing causing abrasive damage. This area is the only part of the site investigated that has distinct deposits of clay loams (figure 140). All of zone B's clay deposits lie at the base of the slope in an area dominated by bullets in poor condition (figure 141).

The soil in this zone is more compact, will have restricted drainage, and the soil will have a higher cation exchange capacity due to their negative charge and ability to exchange with cations on the surface of soil particles (see section 2.3.3.3). The combination of clay loam and slight acidity in this zone may also have impacted on the preservation of the bullets. As Gilbert's work revealed, it is a combination of clay and acidity which creates an inhospitable environment for metal. Lead can suffer severe corrosion in moist acidic clays, developing faults and localised corrosion (Gilbert 1946, 163). It is likely that a combination of slight acidic damp clays in a cultivated waterlogged area of the site is to blame for the poor condition of bullets in this zone.

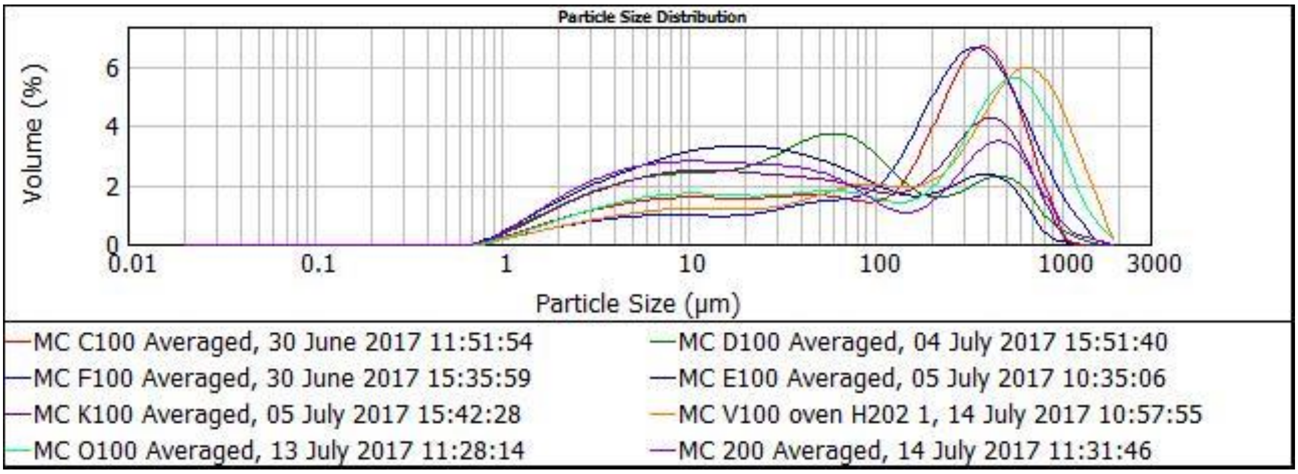


Figure 140: Results of texture analysis for Zone B of Field C, showing the presence of both sands (>60μm) and clays (<8μm) for each sample analysed.

5.8.3.3 Zone C

The pH of topsoil in zone C ranges from 5.59 to 6.03, with an average of 5.85±0.23. Conductivity ranges from 74.97μS/cm to 123.33μS/cm. Water content ranges from 13.48% to 19.6%, and organic content ranges from 5.68% to 8.21%. Samples were predominantly sandy loams, apart from the topsoil at the southern end of the zone which was clay loam, though turned to sandy loam lower down the soil column. One sample was recorded for nitrate content, at 265.7mg/kg, and chloride content was 90.95mg/kg.

Preservation in zone C is generally good, with no bullets scoring a 4 for poor condition in any category. There is a cluster of bullets in very good condition to the north of the zone. This zone is slightly acidic with relatively low conductivity levels and moderate water content. It is predominantly sandy (figure 142), similar to zone A which also showed good overall preservation. Comparing the condition of bullets in this zone to the rest of the site, it would be expected that due to the cultivation of the field and the low topography in this zone, the bullets would be in worst condition than they have been found. Their position away from the steep scarp and on an area of flat land may have aided their preservation.

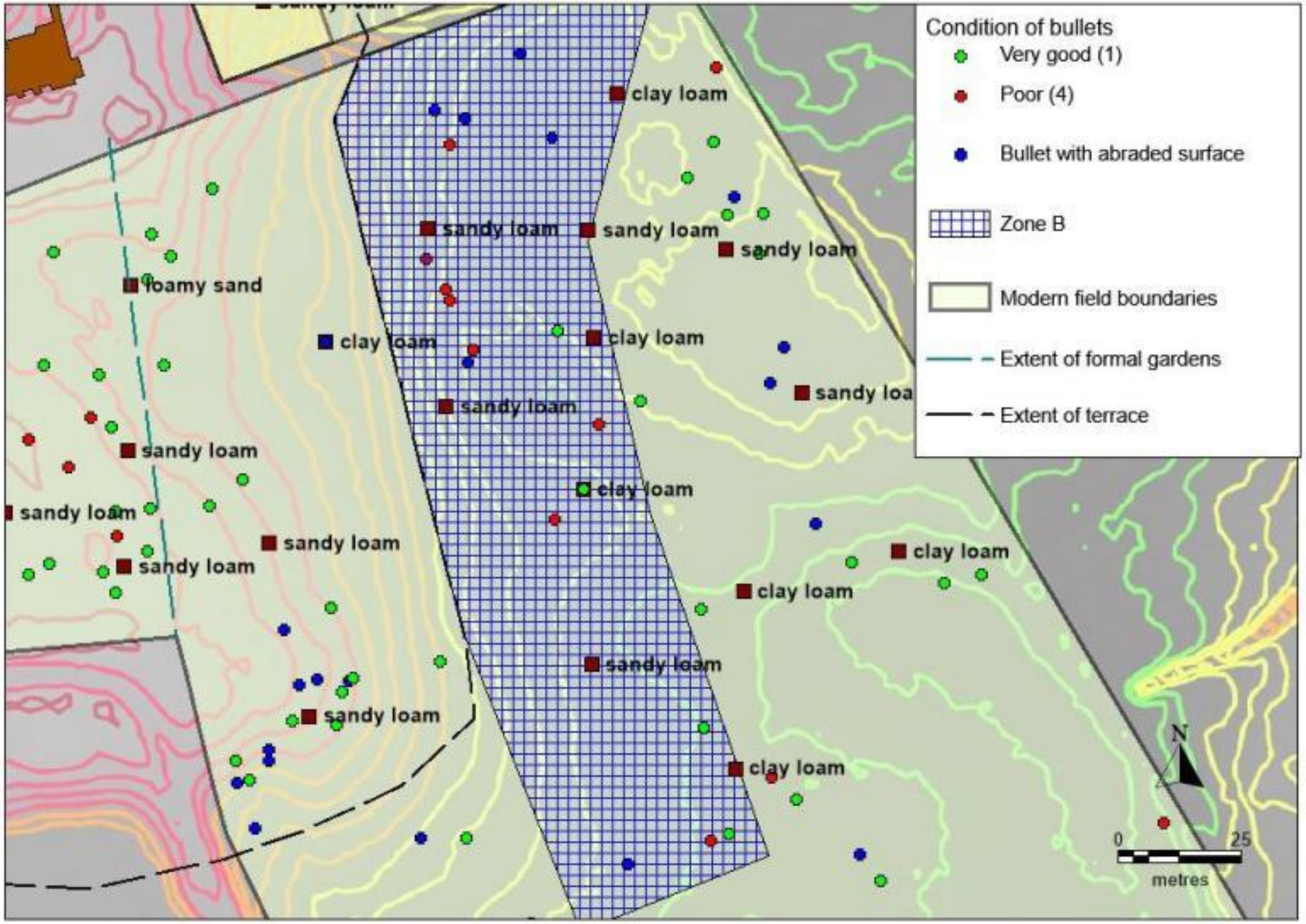


Figure 141: Zone B in Field C showing distribution of bullets and texture of topsoil samples. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

When statistical analysis was carried out on the soil parameters from Zone C against the condition of bullets, no relationships were found to be statistically significant, though two parameters showed slight correlation. Slight negative correlation was present between the pH of the soil and the condition of bullets; as the pH increased, condition score dropped and condition improved (figure 143). The correlation coefficient for this relationship is -0.421 which suggests some correlation, though this value is not statistically significant (table 52).

Slight positive correlation occurred between the conductivity of the soil and the condition of bullets; as conductivity increased, condition worsened (figure 144). The correlation coefficient for this relationship is 0.437 (table 53), and though this value does suggests some correlation, it is not statistically significant due to the low number of samples.

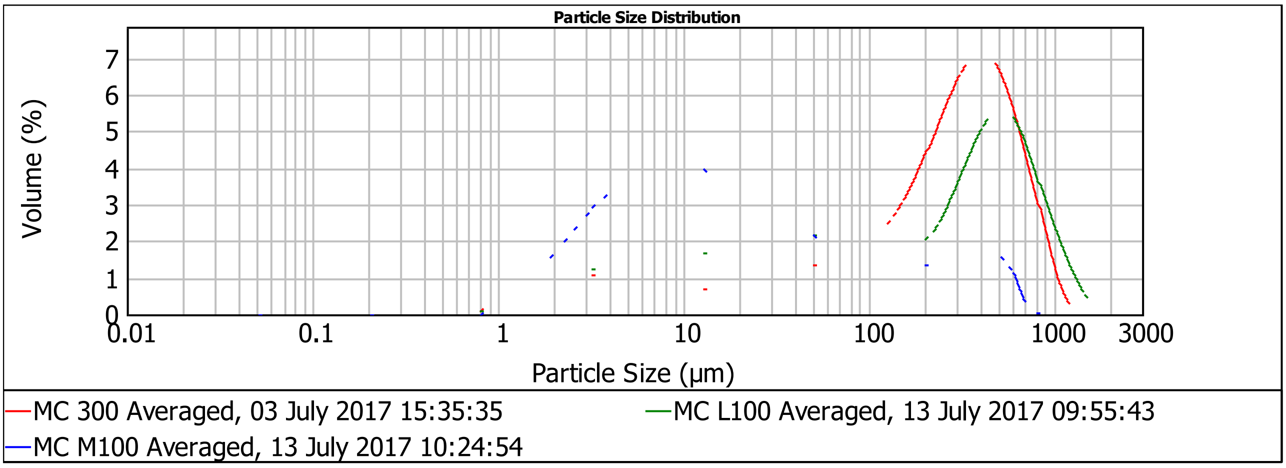


Figure 142: Results of texture analysis for Zone C, with two sandy loams and one clay loam result.

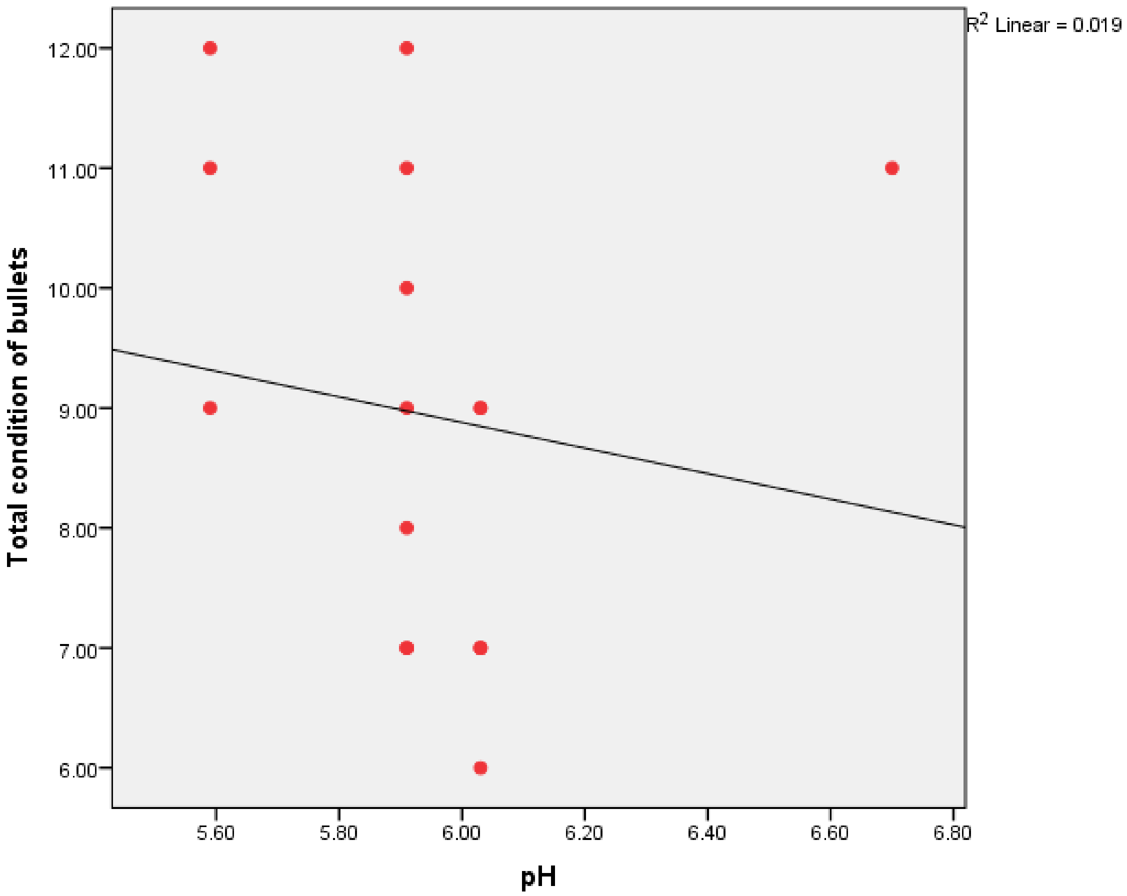


Figure 143: Scatter plot showing slight negative correlation between the pH of the soil and the condition of bullets in zone C of Field C.

			Condition	pH
Spearman's rho	Condition	Correlation Coefficient	1.000	-.421
		Sig. (2-tailed)	.	.092
		N	17	17
	pH	Correlation Coefficient	-.421	1.000
		Sig. (2-tailed)	.092	.
		N	17	17

Table 52: Spearman's rank correlation coefficient of negative value between pH and condition of bullets in zone C of Field C. The value of -0.421 shows correlation but is not significant.

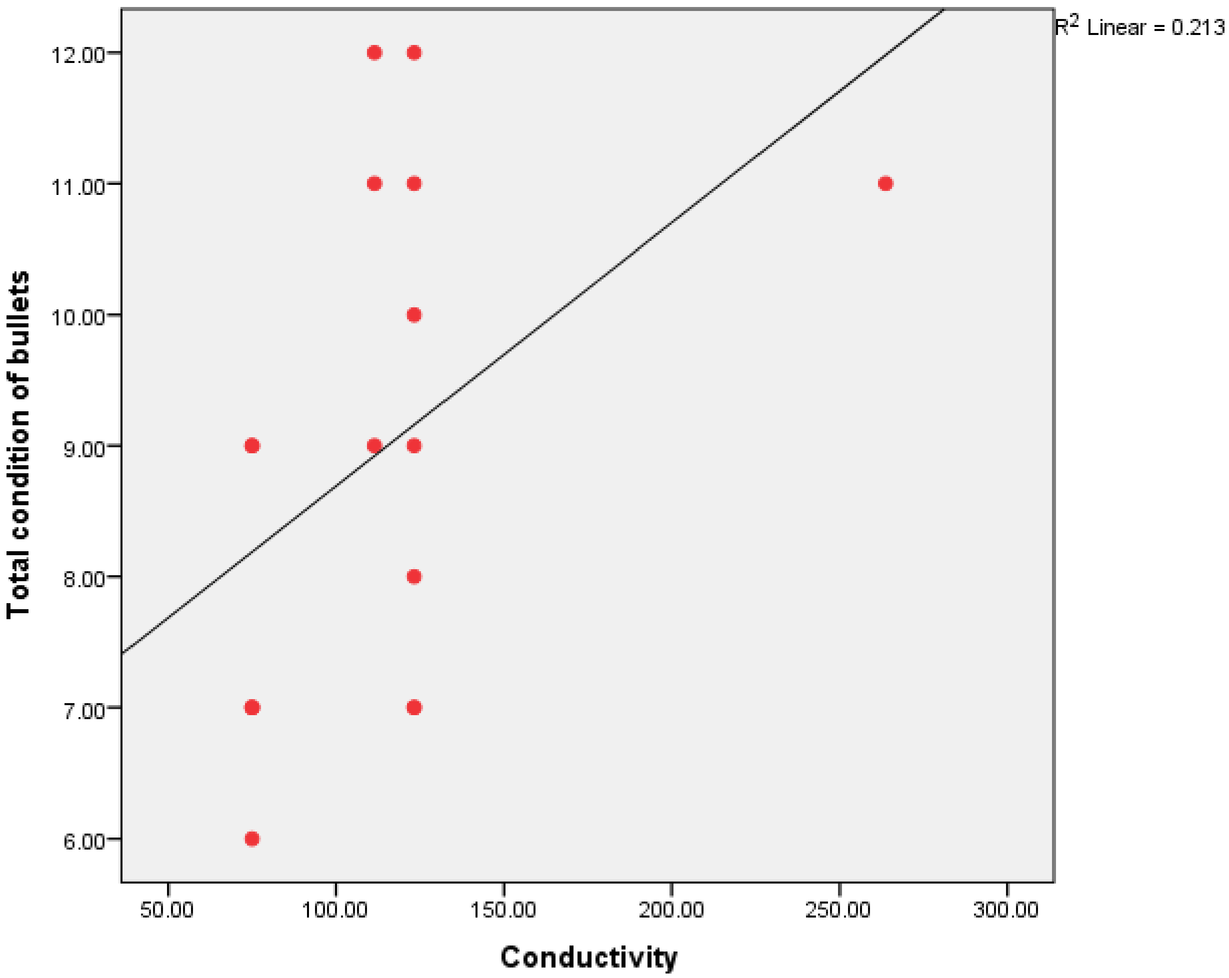


Figure 144: Scatter plot showing slight positive correlation between the conductivity of soil and the condition of bullets in zone C of Field C.

			Condition	Conductivity
Spearman's rho	Condition	Correlation Coefficient	1.000	.437
		Sig. (2-tailed)	.	.079
		N	17	17
	Conductivity	Correlation Coefficient	.437	1.000
		Sig. (2-tailed)	.079	.
		N	17	17

Table 53: Spearman's rank correlation coefficient between soil conductivity and the condition of bullets from Zone C of Field C. The value of 0.437 shows slight positive correlation but is not statistically significant.

5.9 Overview of the siege site of Moreton Corbet

Analysis of the siege site of Moreton Corbet has revealed some interesting patterns in the landscape and between the preservation of lead bullets and the soil environment. The two main parameters which appear to influence the condition of bullets at this site are land use and topography. Bullets are found in better condition in upslope areas of the site, and also in areas where very little cultivation has taken place.

Though few statistically significant patterns have been found, areas of good and poor preservation have been identified in Fields B and C. In Field B, good preservation dominates the western upslope end of the field that was a grassed track way up until 2014. Even though this area of the field is more acidic than the eastern side, conductivity is relatively low and the texture of the soil is mainly sandy loams, creating a well-drained environment. However, it appears that the lack of cultivation plays the greatest part in preservation in this area with no evidence for bullet abrasion.

Field C shows variation in soil conditions and bullet condition. Zone A of Field C indicates that bullets lying upslope suffer less abrasion damage. Even though this area is slightly acidic, it does not appear to have compromised the preservation of the bullets. It is also significant that this zone resides in the former formal gardens of the castle which forms a flat plateau. The lack of abrasion in this area is likely to be the result of a raised soil layer created by the garden allowing bullets to settle lower down in the soil column partly protecting them from plough damage. The area with the worst preservation is zone B of Field C which is down slope of the steep scarp. This zone exhibits slightly higher water contents and clay contents in an area that becomes waterlogged frequently causing drainage issues. The higher content of clay will also allow greater cation exchange capacity and greater exchange of ions in soil solution which may have accelerated the corrosion of bullets.

This site has shown that many factors come into play when examining the preservation of archaeological artefacts. Organic content levels may not have such a dramatic effect on the long term preservation of lead as they tend to impact on early stages of corrosion rather than later stages (Angelini *et al*. 1998). This is also likely to be the case for nitrate levels as they will cause the most damage immediately after fertiliser application; as the data above shows, nitrates get leached out of soil columns quickly.

pH has always been known to have a damaging effect on metal artefacts, but seems to play a minor role at this site as the best preserved bullets are found in areas which are slightly more acidic. The dominating factors in preservation appear to be slope, soil texture, and land use. Bullets are consistently in better condition in upslope areas of the site. The sand content of the soil has enabled abrasion to develop on some of the bullets, though areas down slope where clay content increases are in worst condition due to the combination of damp, aerated, slight acidic clays which will promote the corrosion of lead. Bullets in down slope regions are also under the influence of fluctuating water table, as witnessed during field work.

Ploughing appears to be the most damaging parameter on the preservation of bullets. Ploughing will have mobilised bullets in the soil, allowing a greater flow of oxygen and water, and as bullets come into contact with sand particles, this will enable abrasion to persist on the surfaces of the bullets. Abraded bullets are then more prone to develop localised corrosion and their condition will deteriorate. This process is visualised in figure 145. This site perhaps suggests that the conversion of grassland to arable has accelerated the deterioration of lead bullets in the soil. The small track way area that has been retained as pasture up until 2014 shows much greater levels of preservation. However, more data would need to be available from permanent pasture fields from this site to support this theory.

This site has shown that by analysing the landscape and historic land use of fields, zones can be formed which exhibit patterns in soil conditions without the need for extensive soil analysis. Fields B and C were both segregated and analysed in zones based on topographical features in the landscape and on how the fields had been utilised. This resulted in an effective designation of distinct regions of the landscape. Some soil attributes could be predicted from this landscape assessment; i.e. that water content of soils will be lower in higher regions of the site. However, attributes such as soil pH cannot be presumed simply by looking at a landscape and this study has shown that by taking soil samples systematically in specific topographical zones, patterns of association can be identified between the burial environment and lead bullet preservation.

Though statistical analysis on a site level did not achieve significant results, spatial analysis highlighted the relationship between the preservation of bullets and the soil environment at this site. It may be the case that the sample of bullets analysed was too small to form statistically significant results. Chapter 8 will address all three sites as a collective and the result is statistically significant correlations between soil environments and lead bullet preservation.

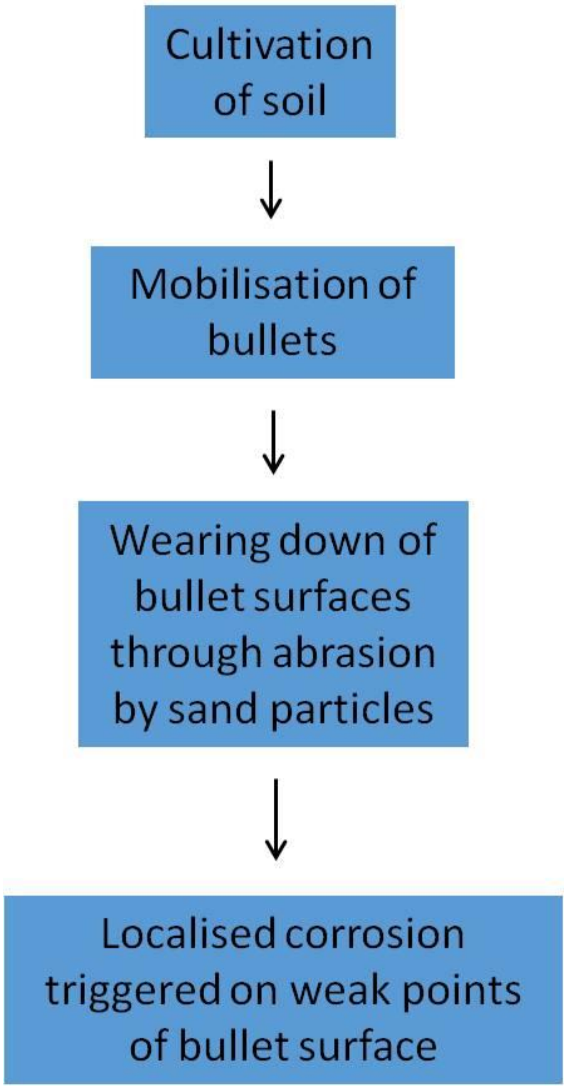


Figure 145: Likely corrosion trajectory of bullets in Moreton Corbet soils, triggered by the cultivation process.

6 Edgehill battlefield

6.1 Introduction

The first battle of the Civil War was fought at Edgehill in 1642, involving armies of over 10,000 troops on both the Parliamentarian and Royalist sides (Foard 2012, 126). The site of Edgehill near Kineton in Warwickshire covers an area approximately 12km² and is a registered battlefield due to its significance in conflict history. Due to the extent of the conflict the landscape was littered with artefacts from the time of battle. Several metal detecting surveys have been carried out on the site since the 1960s, including a survey by the Glasgow University Archaeology Research Division (GUARD) in 2002. The most recent and extensive survey was carried out between 2004 and 2007 over 144 days where 3,250 artefacts were retrieved from the site, of which 1,096 were lead bullets (Foard 2012, 154) (figure 146). The finds database was kindly provided for analysis by Dr. Glenn Foard.

The site of Edgehill was chosen for the present study partly due to the volume of data available from the site. It had previously been noted that the lead bullets were in particularly good condition for a battle assemblage (Foard 2012, 119). This makes a useful comparison to the collection at Wareham which is known to be in a much worse state of preservation (see chapter 7). The soil and superficial geology is also very different to the other two case studies in this study, being slightly alkaline clays and therefore provides a different burial environment for comparison.

The locations of objects were recorded using GPS accurate to the nearest 0.60m and collected systematically during the detecting survey in clear plastic bags. They have been stored as individual finds in airtight boxes with silica gel and humidity strips at a relative humidity <40% since the survey at the University of Huddersfield, as advised by standard procedures (Rimmer *et al.* 2013, 13). As the battlefield is registered, permission was obtained from Natural England and Historic England to carry out test pitting at the site. A large section of the battlefield is now under the jurisdiction of the Ministry of Defence and so this area was omitted from the study due to difficulties in access for fieldwork.

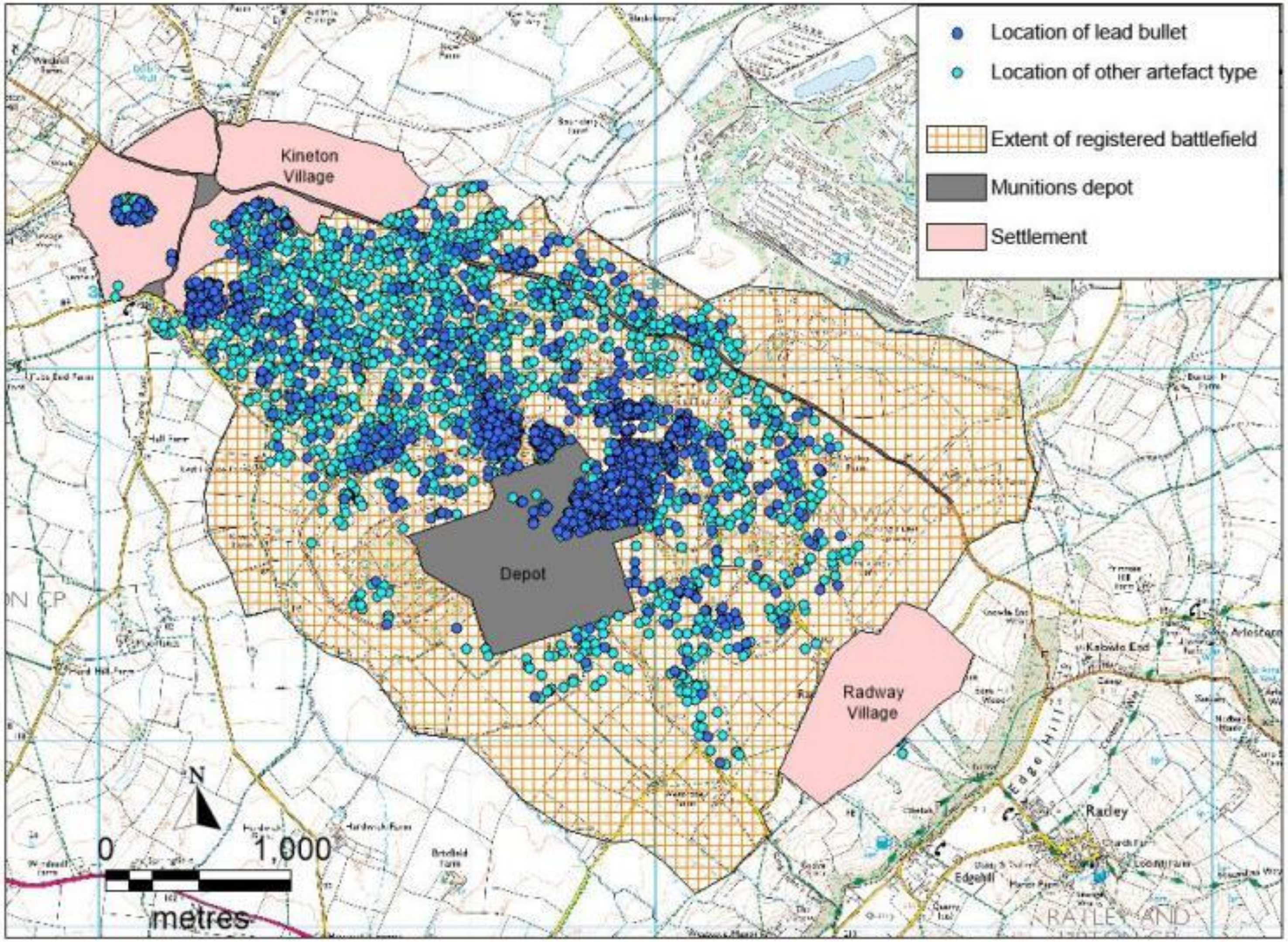


Figure 146: Landscape of Edgehill showing extent of battlefield and location of all artefacts and lead bullets. Base map Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service.

6.2 Landscape

The battlefield lies in a fairly flat terrain with the dominating ridge 'Edge Hill' to the south east. This ridge rises to a height of 215m AOD which was a significant feature used during the battle by the Royalists and which gives the battlefield its name (Foard 2012, 129). Most of the battlefield under investigation lies approximately 80-90m AOD. The bedrock is Charmouth mudstone, part of the Blue Lias formation consisting of mudstone and limestone, overlaid by superficial deposits of clays and loams (British Geological Survey 2017).

6.3 Field methodology

The area studied in this research covers six fields across approximately an area of 2.5km². Fields were chosen based on their historic and current land use, the distribution of lead bullets, and to avoid contaminated areas of the site from the construction of munitions depots and railway lines (figure 147). Initial fieldwork was carried out at the site in April 2015. Two 1mx1m test pits were excavated in the ridge and furrow of Field A in order to assess the nature of deposits and the difference between the higher ridge and lower furrow deposits. Upon excavation the subsoil was found to be very compact and dry and so excavation was restricted to one corner to expose the soil profile, with lower deposits extracted using a Dutch auger (figure 148). The test pit was dug to a depth of 0.38m, but the remaining deposits were extracted by auger to a depth of 0.80m (figure 149).

All deposits comprised silty clay, becoming lighter in colour and becoming more compact with depth. Deposit 101 appeared to be a buried post medieval ploughsoil where a single piece of medieval pottery was retrieved. Test pit II was excavated 3.5 metres to the west of test pit I in the base of the adjoining furrow. The same issue occurred with compactness of the ground and so another section was dug to expose the soil column. Samples were taken from the profile of the test pit starting from lower deposits working upwards so the deeper deposit would not be contaminated by falling debris (figure 150). This exercise revealed how soil samples could be effectively taken from the profile, though it was decided that digging a 1mx1m test pit for soil samples was far too time consuming and resulted in too much disturbance and damage to the field. For future soil sampling the same approach for Moreton Corbet was adopted by digging 0.30mx0.30m pits and augering lower deposits. Test pit locations were based on the field, variations in slope and terrain, and vicinity to bullet locations.

A total of 22 test pits were excavated over 6 fields on the site, focusing on areas of lead bullet clusters. Due to the size of the site an intensive field by field survey could not be conducted as it was outside the scope of this project. The site of Moreton Corbet, discussed in chapter 5, has an assemblage retrieved from a much smaller area and it was possible to carry out detailed sampling of the fields. However, data at Edgehill is much more dispersed and sampling had to be conducted over a much wider area. The differences in soil sampling across the two sites will help to establish what level of soil sampling is required to characterise soils across landscapes of varying size.

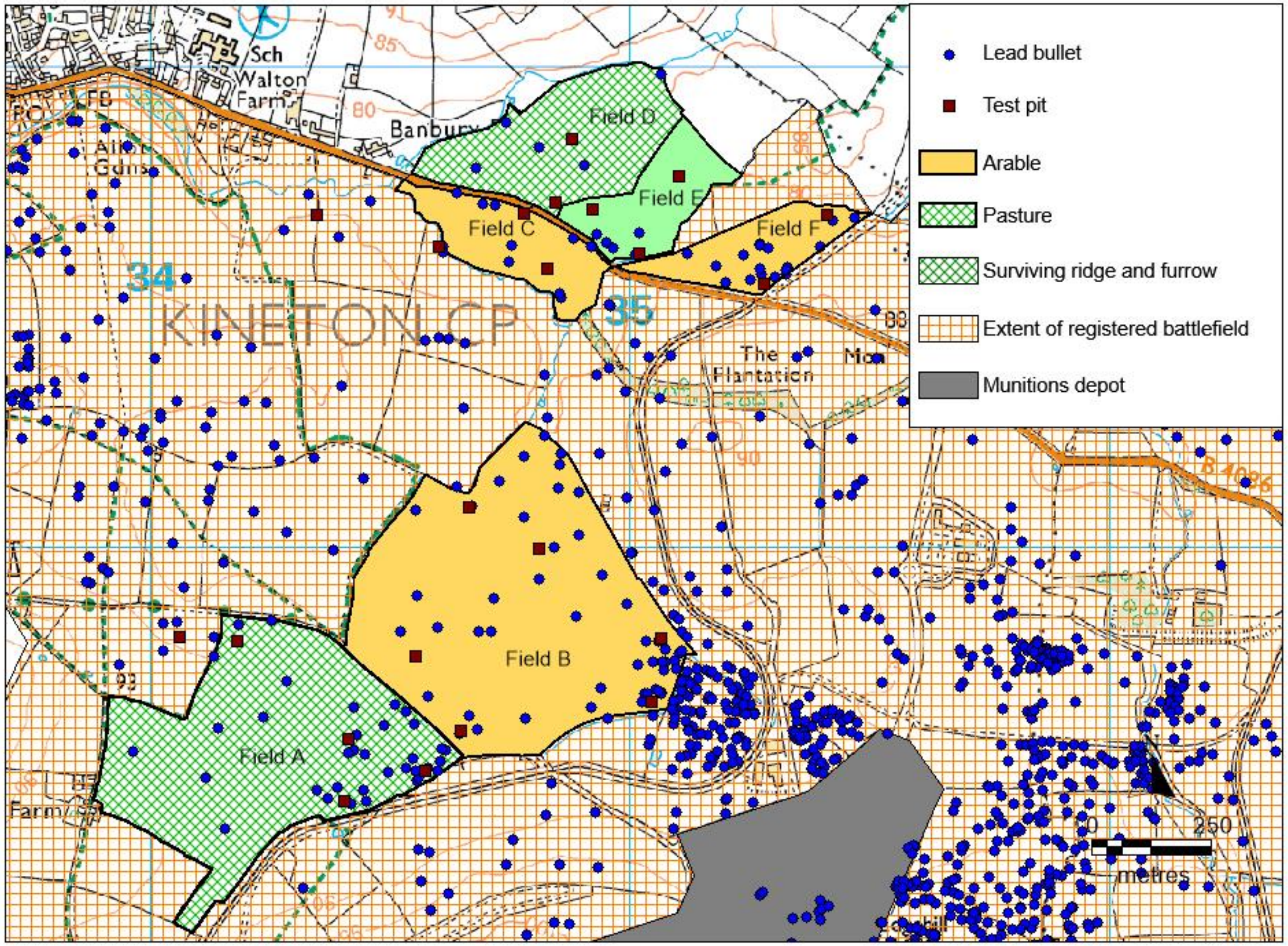


Figure 147: Location of six fields under investigation in this study showing location of lead bullets, test pits, extent of surviving ridge and furrow, and current land use. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service.

Figure 148: Test pit I after removal of topsoil 100 and cleaned to subsoil 101, revealing clay deposit 102 in SW corner (top right), taken from north.

Edgehill 27.05.2015
Test Pit I
North Facing Section
S. Rowe
Scale 1:10

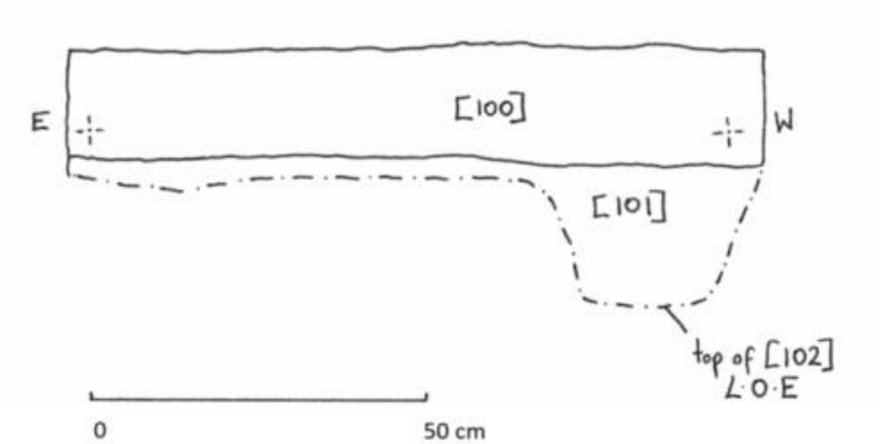


Figure 149: Section drawing of test pit I showing depths and contexts.

Figure 150: Extraction of soil samples from the soil profile at Edgehill, working from bottom to top.

6.4 Historic land use assessment

A land use assessment was carried out for each of the six fields under investigation to establish how they have been utilised since the time of battle. An extensive landscape assessment has already been conducted by Foard and will be summarised here (Foard 2008a).

The Edgehill landscape was under open field cultivation by the 14th century. Due to a lack of documentary evidence it is impossible to identify which fields had been converted to grass by the time of the battle in 1642 (Foard 2008a, 192). By the early to mid 18th century, and in some cases before the 1642 battle, most of the landscape around Kineton and Radway village had been enclosed and converted to pasture. The battlefield contains the best surviving medieval ridge and furrow from any English battlefield (Foard 2008a, 191-192). The quality and extent of the ridge and furrow can be used to identify the extent of uncultivated land and it appears that large parts of the landscape have remained in pasture since at least the 18th century up until at least the late 1950s once ploughing began after the Second World War (English Heritage 1995; Foard 2008a; 2012, 132). It is only during the 1970s and 1980s that fields begin to be cultivated in the current study area, though pasture remains the dominant land use.

The battlefield was retained under pasture in 1937 when the land utilisation survey of Great Britain was carried out (Ordnance Survey of England and Wales 1937). By the 1947 RAF aerial photograph verticals all the fields still contained distinct ridge and furrow and appear to still be under pasture, apart from Field F which has already lost its ridge and furrow. By the early 1990s three fields are clearly under arable cultivation and have been for several years; fields B, C and F have been ploughed and all trace of ridge and furrow has been lost in Fields C and F, though Field B still has traces of ridge and furrow. Field observations in 2014 and 2016 revealed that distinct ridge and furrow only now exists in fields A and D (figure 151).

Field A is a permanent pasture field lying in a high level stewardship scheme which restricts any ploughing or use of fertilisers on the field; only natural manure has been applied in the last twelve years of the current farmer's occupancy (Jackson Pers. Comm. 01.05.2015). Field B however has been under the plough for at least the last three decades and all ridge and furrow has been destroyed. The battlefield now comprises areas of arable and long term pasture where traces of ridge and furrow remain. Edgehill thus provides an ideal opportunity to assess the degree to which, if at all, recent conversion to arable cultivation has impacted on the preservation of lead bullets in the ground. Historic Land use across the site is summarised in table 54.

Figure 151: View across ridge and furrow in Field A, from north east.

Field	Land use	Source	Date
All	Pasture	Land Utilisation Survey of Britain, Stratford on Avon sheet 82(Ordnance Survey of England and Wales 1937)	1937
A **B** **C** **D** **E** **F**	Pasture r+f Pasture r+f Pasture r+f Pasture r+f Pasture r+f Pasture no r+f	(Aerial photograph RAF/CPE/UK/1926 2120 1947; Aerial photograph RAF/CPE/UK/1926 2096 1947)	1947
A **B** **C** **D** **E** **F**	Pasture r+f Pasture r+f Pasture r+f Pasture r+f Pasture r+f Pasture?	(Aerial photograph RAF/542/16 27 1954)	1954
A **B** **C** **D** **E** **F**	Pasture r+f Arable and pasture r+f Pasture? Pasture r+f Pasture Pasture Pasture?	(Aerial photograph RAF/58/4649 25 1961)	1961
A **B** **C** **D** **E** **F**	Pasture r+f Arable Arable (no r+f) Pasture r+f Pasture Arable	(Aerial photograph OS/93292B 215 1993; Aerial photograph OS/95140 169 1995)	1993-5
A **B** **C** **D** **E** **F**	Pasture r+f Arable (no r+f) Arable (no r+f) Pasture r+f Pasture (no r+f) Arable (no r+f)	Field observations	2014-2016

Table 54: Land use assessment of all investigated fields. ('r+f' = ridge and furrow).

6.4.1 Field A

Field A has seen no change in field boundaries or land use since at least the 1930s based on aerial photographic evidence (figure 152). It is likely, due to the excellent preservation of the ridge and furrow in this field, that it has not been cultivated at least since the enclosure of Little Kineton in 1733 (Foard 2012, 133). Its long term pasture use presents an excellent opportunity to address the preservation of lead bullets in a field where no cultivation has taken place in modern times.

6.4.2 Field B

Field B has lost several hedge boundaries since the 1930s. On the 1947 RAF aerial photographs, several hedge boundaries are in place forming five distinct fields (Aerial photograph RAF/CPE/UK/1926 2120 1947). At this time distinct ridge and furrow is still visible across the field, suggesting it had not been cultivated since at least 1733. The hedge boundaries stay in place, even when one section is brought under the plough in the early 1960s. By the early 1990s, only the central boundary is still intact and has been amalgamated into a single cultivated field (figure 153). It is likely the field was cultivated in the late 1970s to early 1980s when the UK joined the EEC in 1973 with the subsequent promotion of converting more land to arable (Robinson and Sutherland 2002). By the early 1990s all trace of ridge and furrow has been lost.

6.4.3 Field C

Field C is bordered to the north by the B4086 road and to the south by the river Dene and as a result has not changed in shape or field boundaries since at least the 1930s (figure 154). Distinct ridge and furrow is still present on the RAF 1947 aerial photographs indicating that it had not been cultivated since the enclosure of Great Kineton in 1789 and most likely earlier as Fields C, D, E, and F were already enclosed in 1789 (Aerial photograph RAF/CPE/UK/1926 2120 1947) (Foard 2012, 129). The field remains in pasture use until the 1980s to early 1990s when it was converted to arable and remains in cultivation to the present day. All trace of ridge and furrow has been lost.

6.4.4 Field D

Field D has remained under long term pasture and distinct ridge and furrow is still present in the field. Similar to Field A, it is likely this field has not been cultivated since before 1789.

The only changes to the field have taken place to the southern end. In the 1940s a separate roughly square patch of pasture split Field D into two (figure 154). This pasture area has no ridge and furrow present in the 1940s and therefore must have been ploughed since the battle took place. It appears this southern area of Field D remains in pasture throughout the 20th century, and the hedge boundary is removed in the 1980s (Aerial photograph OS/93292B 215 1993).

6.4.5 Field E

This field was two separate fields in the 1940s. Both areas were under pasture divided by a hedgerow, though the northern field had distinct ridge and furrow surviving, indicating no cultivation since before 1789, in contrast to the southern area. By 1976 this field boundary had been removed. By 1993 no ridge and furrow is present to the north, which suggests it has been ploughed out during the 1980s. By 1993 both fields are in pasture and remain pasture to the present day.

6.4.6 Field F

Field F is the only field under investigation which exhibits only faint traces of ridge and furrow in the 1940s (Aerial photograph RAF/CPE/UK/1926 2120 1947). This indicates that this field had already been cultivated at some point since the 1789 enclosure. Through the 20th century it remains under pasture until it is converted to arable by 1993 and remains under cultivation to the present day (figure 154).

6.4.7 Edgehill landscape

The battlefield of Edgehill resides in an historic landscape that has predominantly been under pasture throughout the post medieval period. It was under open field cultivation during the medieval period and the vast majority was not enclosed until the 18th century when the majority of land was converted to pasture (Foard 2012, 127-135). The fields under investigation in this study have predominantly remained under pasture up until the 1970s to 1980s when part of the landscape was brought under the plough. There are still fields (A, D) where maintaining long term pasture has resulted in the excellent preservation of distinct ridge and furrow. These areas provide an excellent example of lead bullets residing in long term pasture since at least the 18th century.

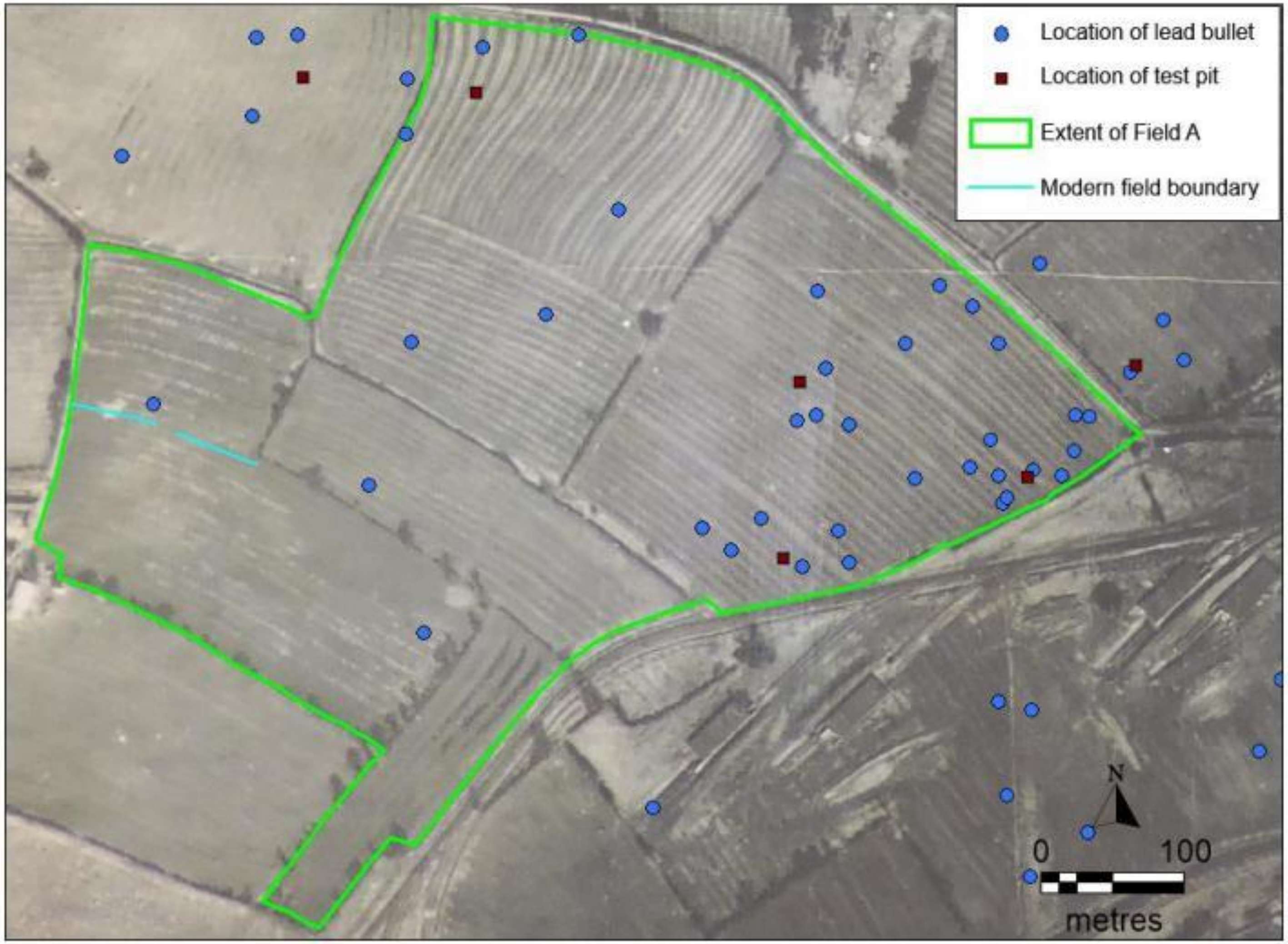


Figure 152: Extent of Field A showing location of bullets and presence of ridge and furrow from 1947 which is still present to this day (Aerial photograph RAF/CPE/UK/1926 2120 1947). ©Historic England aerial photograph.

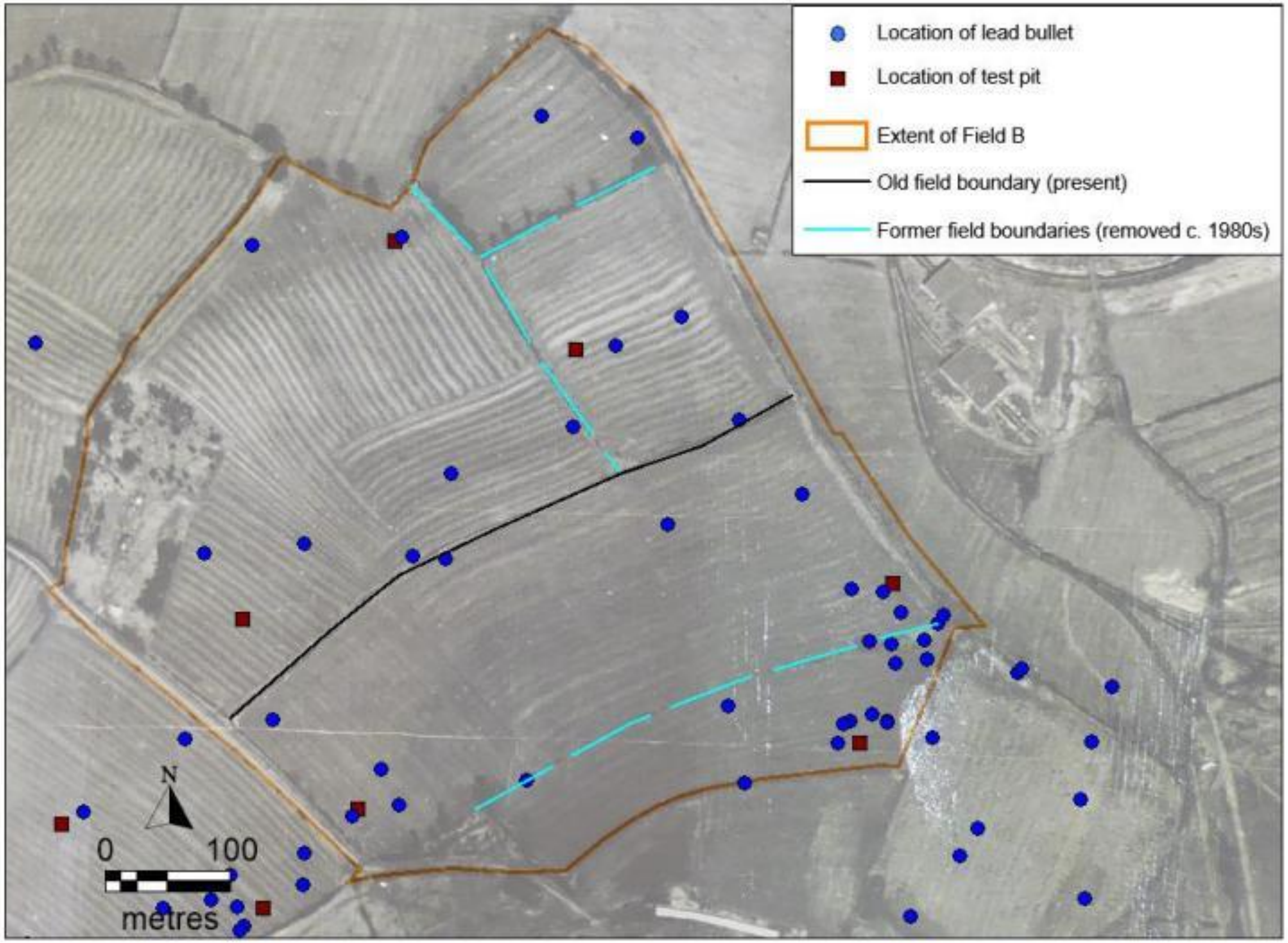


Figure 153: Extent of Field B showing location of bullets and field boundaries which have since been removed. Background shows 1947 ridge and furrow which is now lost (Aerial photograph RAF/CPE/UK/1926 2120 1947) ©Historic England aerial photograph.

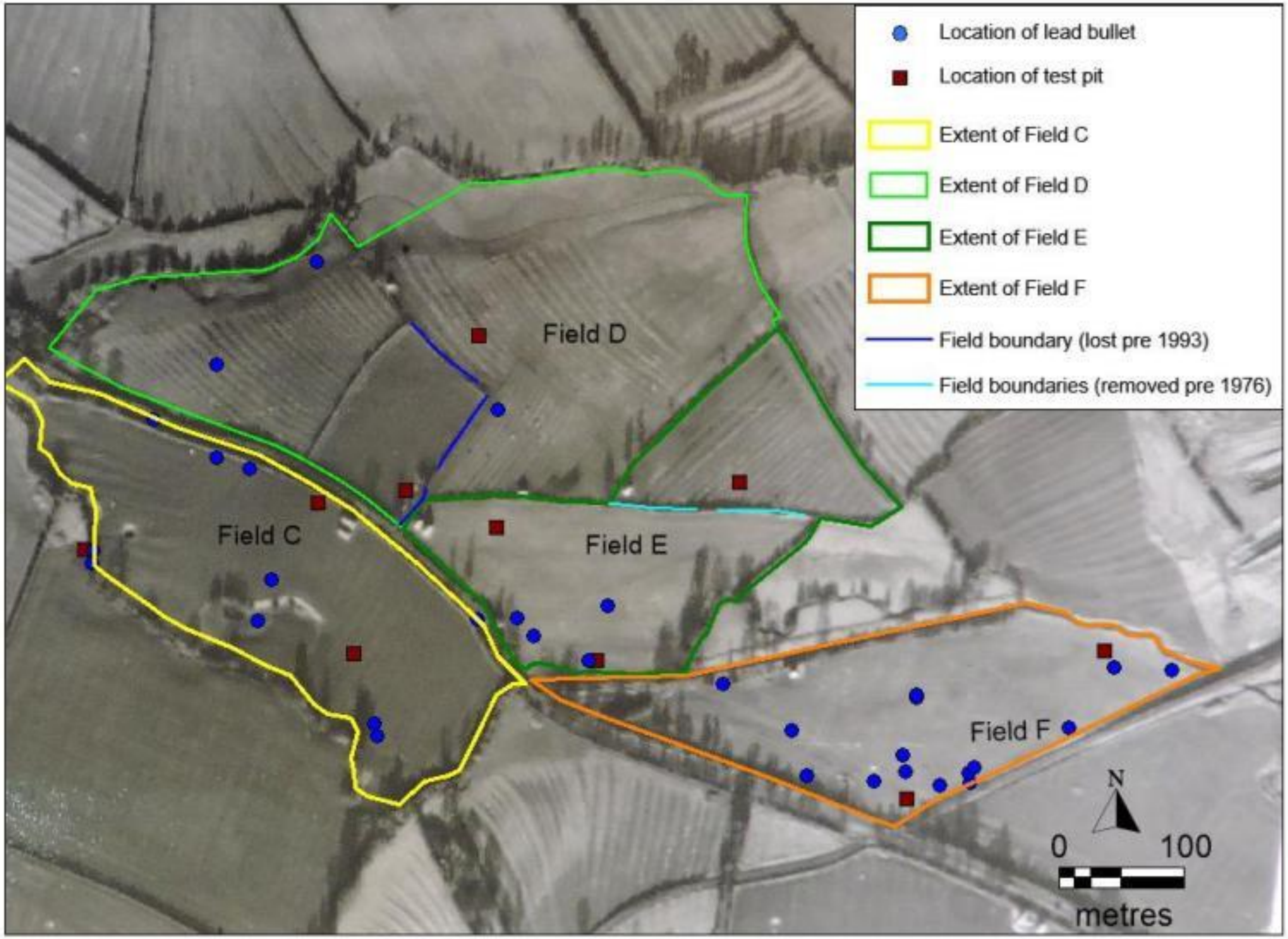


Figure 154: Extent of fields C, D, E, and F showing former field boundaries and the location of bullets. Ridge and furrow is now only present in Field D (RAF 1947; RAF aerial vertical CPE/UK 1926 2094 1947). ©Historic England aerial photograph.

6.5 Lead bullet condition assessment

112 bullets were assessed from Edgehill for their condition; 10% of the total collection from the site. Overall, the bullets are very well preserved. In total, 99% of the bullets assessed were in very good or good condition overall, with no bullet scoring poor in any condition category (figure 155). 94% of the bullets scored between 5 and 8 for the 5 category assessment, with none scoring higher than an 11 out of a possible total of 20 (figure 156). An explanation of how overall condition score equates to the five condition scores is presented in table 55. The majority have a white solid patina with little evidence of pitting corrosion or loss of patina (figure 157).

Analysis of the five condition categories reveals how frequently bullets scored a 1 or 2 for all condition categories (figure 158). Only 1% of the bullets analysed scored lower than a 2 for any condition category, with the exception of 'stability of surface' category where 5% of the sample scored a 3 for fair condition. This reflects how well preserved the collection is in every condition attribute.

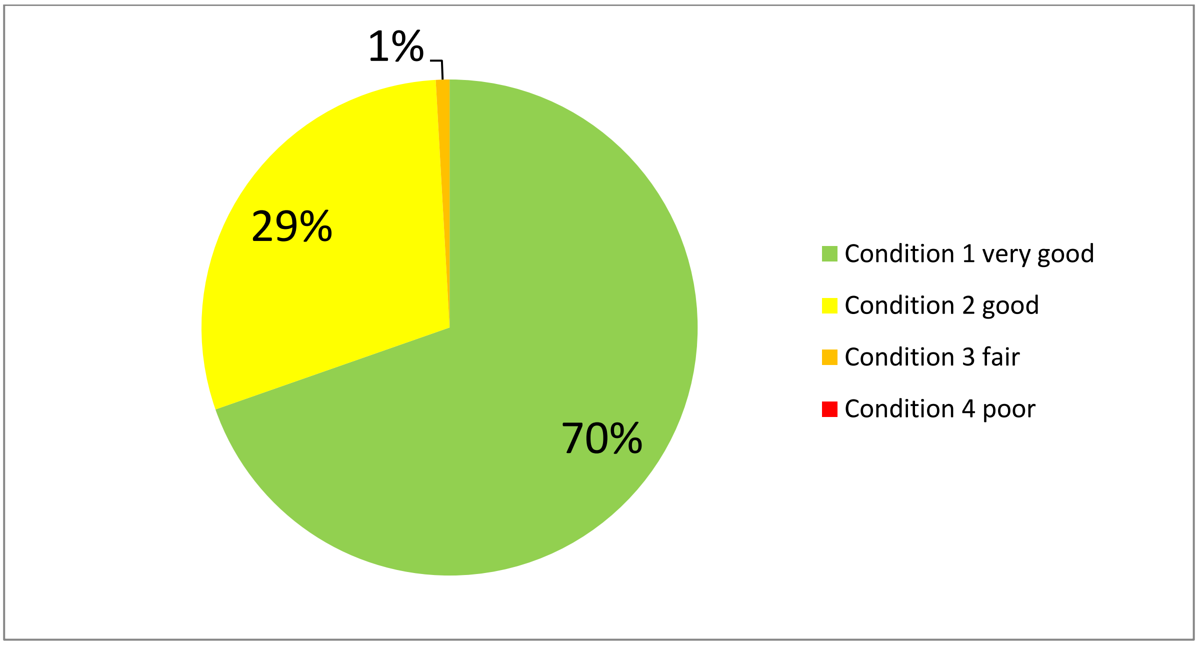


Figure 155: Overall condition of bullets from Edgehill by percentage (%) of total collection sampled.

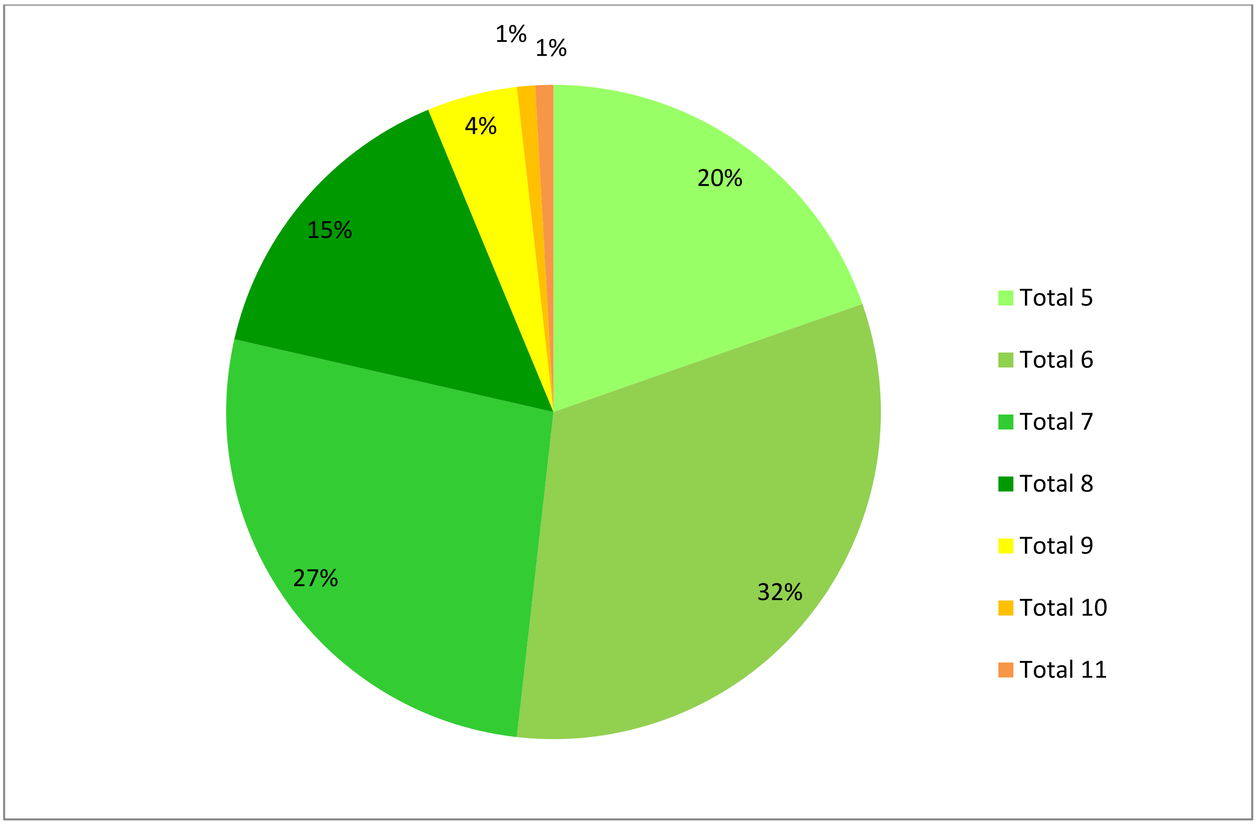


Figure 156: Total scores of bullets from the five condition categories (out of a possible 20) by total percentage of collection studied. The colours equate to the same scoring range as the overall condition score in figure 155).

Condition score	Overall score of lead bullet condition (possible total 4)	Total condition score from 5 condition categories (possible total of 5-20)
Very good	1	5-7
Good	2	8-10
Fair	3	11-13
Poor	4	14+

Table 55: How the overall condition score equates to the total five category condition score of lead bullets.

Figure 157: Example of a bullet from Edgehill with hard stable pale patina (EDG 772).

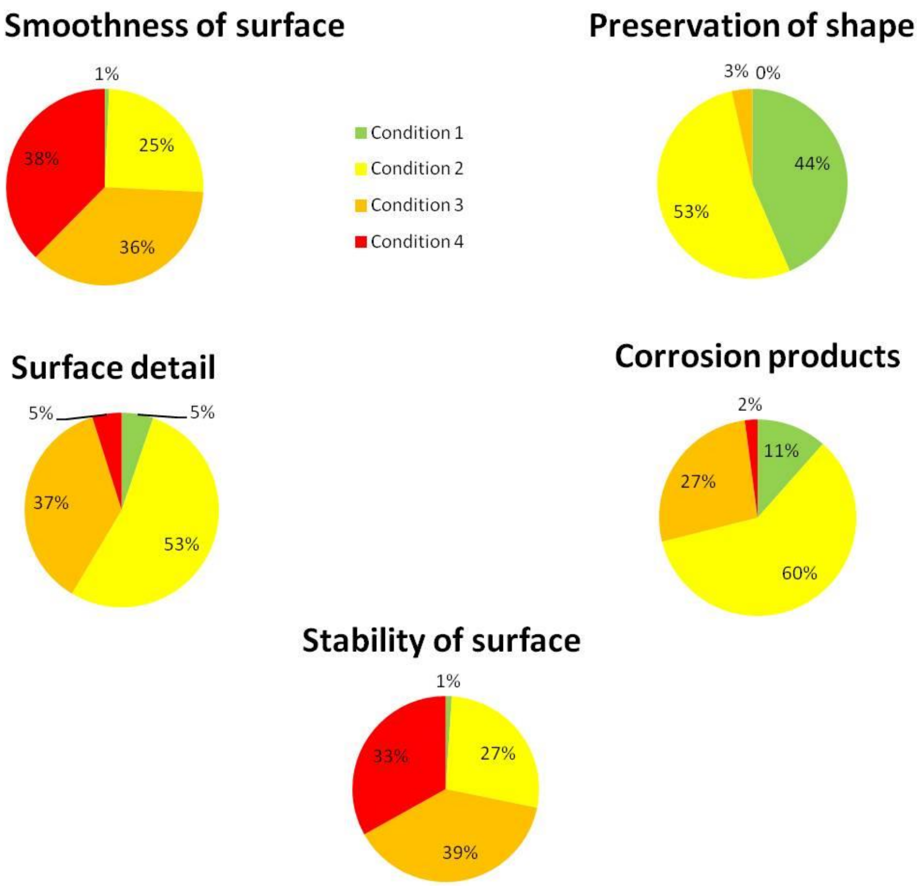


Figure 158: Total number of bullets and their condition score for each of the five category assessments reflecting the well preserved nature of the assemblage.

Further data was collected on certain corrosion attributes of the bullets, the results of which can be seen in table 56. The lack of corrosion issues on these bullets is significant as it contrasts with observations in other assemblages. This may be due to the soil texture. As Dunnell states (1990, 593), objects may move as peds (blocks of soil) in heavy clay rather than as a sole object and the clay particles may act as a protective buffer resulting in less abrasion. The soft small, plate-like structure of clays also makes abrasion less likely as sand particles are large, angular and are known to cause greater abrasive damage to objects, leading to corrosion cracking (Edwards 1996, 91). Only nine bullets showed any significant sign of being abraded on their surfaces; a large contrast with the sites of Moreton Corbet and Wareham which exhibited abrasion on 34% and 55% of the bullet assemblages respectively. Both these sites have soils with much higher sand contents. The site of Edgehill also exhibits different land use history, being under long term pasture for predominant periods and allowing bullets to reside low down in the topsoil without disturbance.

Condition issue	**Total number of bullets studied**	**Percentage of total collection studied**
Hit by plough or spade	3	2.7%
General pitting issues	1	0.9%
Significant localised corrosion	2	1.8%
Significant eroded/abraded surface	10	9%
Significant cracks on surface	0	0%
Powdery surface	0	0%

Table 56: Total number of bullets in sampled collection with corrosion characteristics.

All the bullets from Edgehill are relatively well preserved and in order to assess whether the thickness of their corrosion products had an effect on their preservation, four bullets were measured for their corrosion thickness (table 57). The results indicate that the bullets have relatively thin corrosion products (figure 159). It was suggested from the Moreton Corbet samples that thinner corrosion products left artefacts prone to corrosion, but the bullets from Edgehill have not been abraded even though their patinas are thin. This is ultimately down to their burial environment. Due to lack of abrasion and corrosion, the bullets have yet to develop further corrosion layers. If the bullets from Edgehill were subjected to abrasive sand particles it is likely their thin patinas would develop abrasion issues, and further corrosion compounds would be encouraged to develop. It may be revealed in time after several more years of ploughing whether the clay-rich soil at Edgehill is enough of a buffer against future corrosion damage.

Bullet	Corrosion thickness (averaged from 5 measurements)
EDG 595, condition 2	52±8μm
EDG 2071, condition 1	59±20μm
EDG 2074, condition 2	88±19μm
EDG 2161, condition 1	53±20μm

Table 57: Corrosion thickness of four selected bullets.

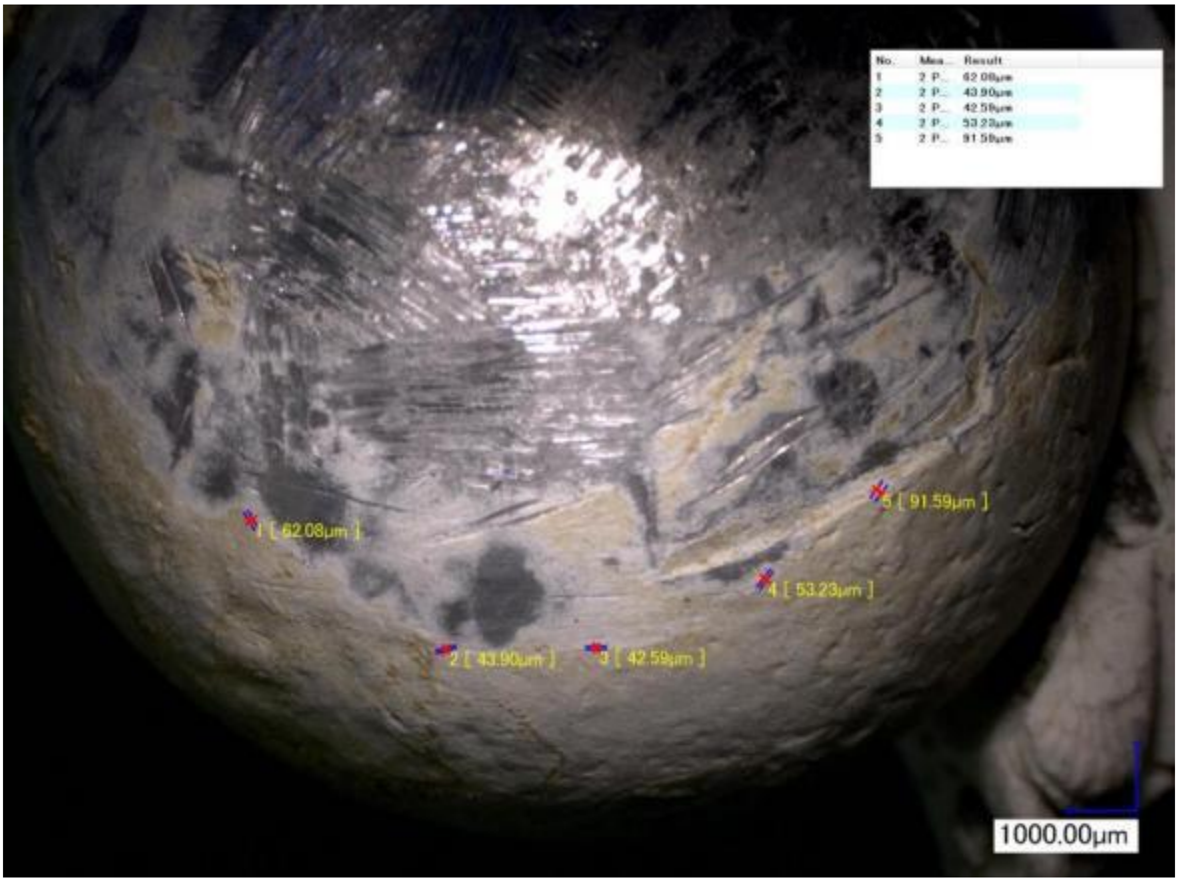


Figure 159: Bullet from Edgehill with relatively thin patina removed for measurement (EDG 2071).

6.6 Bullet composition and corrosion products

21 bullets from Edgehill were analysed using XRF to examine their metallic composition, as laid out in the methodology (4.5.2). The lead content ranged from 89% to 95.7% with an average content of 93±1.8%. Very few trace elements were present in the Edgehill bullets. Tin content ranged from 0.64% to 5.11% with an average content of 1.46±1.26%. As discussed above, the bullets from Edgehill were all well preserved and no significant corrosion issues were identified during analysis. However, it is interesting to note that the only bullet which scored a 3 for overall fair condition also had the second highest tin content of 4.1% (figure 160). This perhaps suggests that the tin content may have affected the bullet's preservation.

In order to examine which corrosion products have formed on the bullets during their time in the ground, six of the bullets were selected for X-ray diffraction (XRD). All sampled bullets exhibited the formation of standard lead compounds such as cerussite, hydrocerussite and litharge, which will form stable solid patinas on the surface of the bullets protecting the metal from further corrosion (figures 161-172). However, one bullet (EDG 2161) comprised predominantly chloropyromorphite and cassiterite. This bullet contains 5.11% tin at its core, which has resulted in the formation of the SnO_2 compound cassiterite. This bullet has formed a tin compound rather than a lead compound which has not compromised its condition. Cassiterite is a protective tin compound, similar to cerussite for lead and its formation has continued to protect the underlying metal from corrosive attack and the bullet still scores very good for overall condition with a smooth stable patina. Apart from this one bullet exhibiting tin compounds, the dominant product for all other bullets is cerussite which has formed a stable solid protective patina on the bullets leaving them in very good or good condition.

However, if the compounds are compared to those formed on bullets from Moreton Corbet, we see that cerussite has not formed a fully protective barrier to further decay. At Moreton Corbet, two bullets formed a layer of cerussite, but scored a 3 or 4 for overall condition indicating that the formation of cerussite had failed to preserve the bullets in the long term (see section 5.6). This difference in preservation at the two sites suggests that other environmental factors are responsible for their deterioration and protective compounds will only stabilise lead in certain environmental conditions. It is likely that the lack of abrasion at Edgehill has provided stability to the thin cerussite patinas.

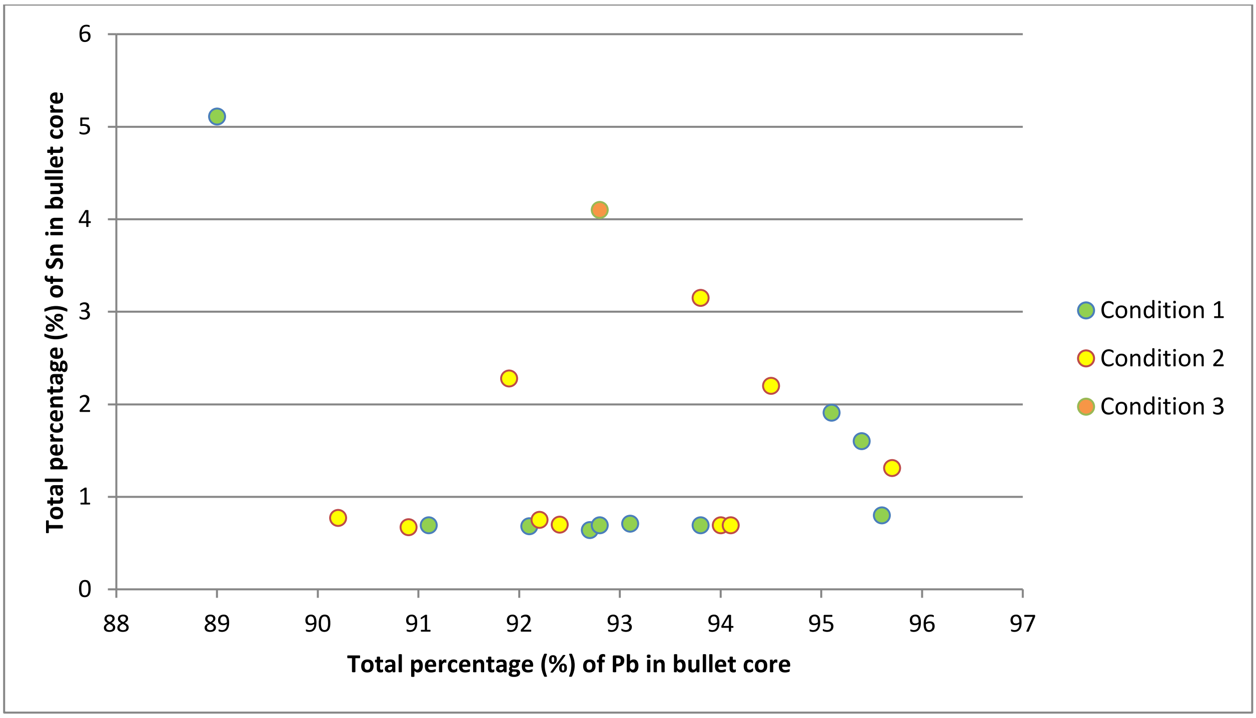


Figure 160: Total percentage of lead (Pb) and tin (Sn) in the core of bullets from Edgehill and their corresponding condition scores.

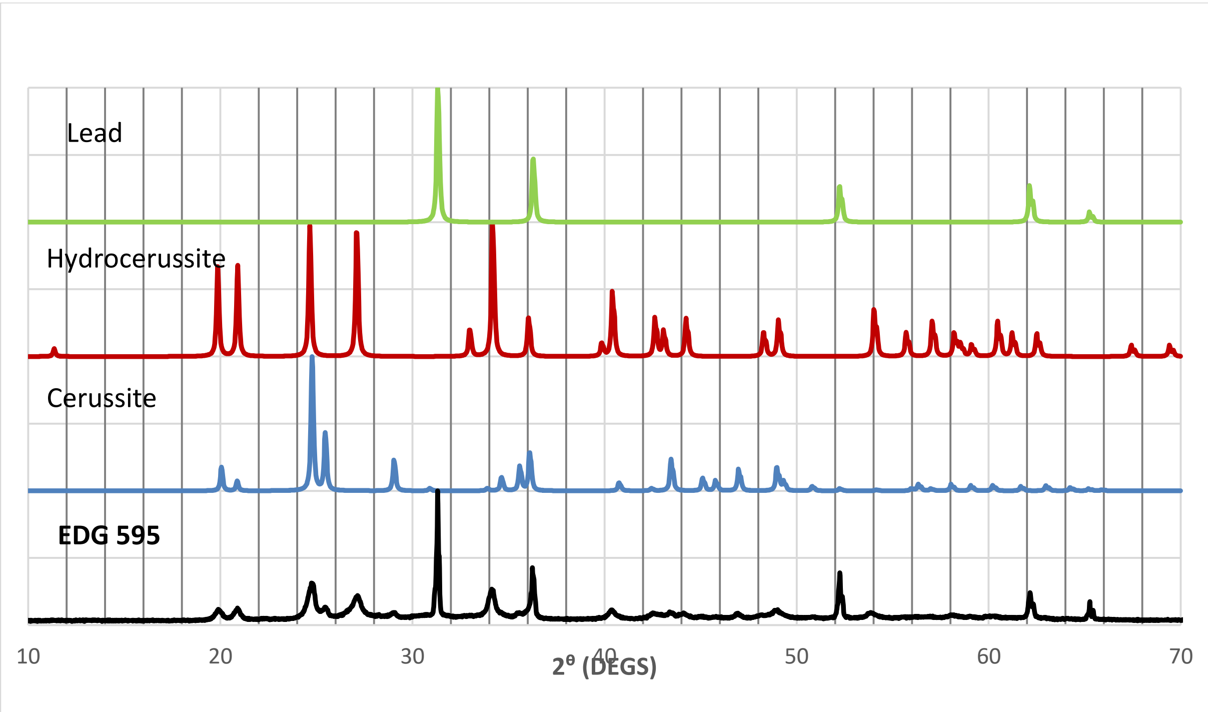


Figure 161: XRD spectra for bullet EDG 595. The main compounds present are cerussite and metallic lead with a trace amount of hydrocerussite. This bullet contains 92% lead.

Figure 162: Bullet EDG 595 with slightly rough but stable surface. Condition 2, good.

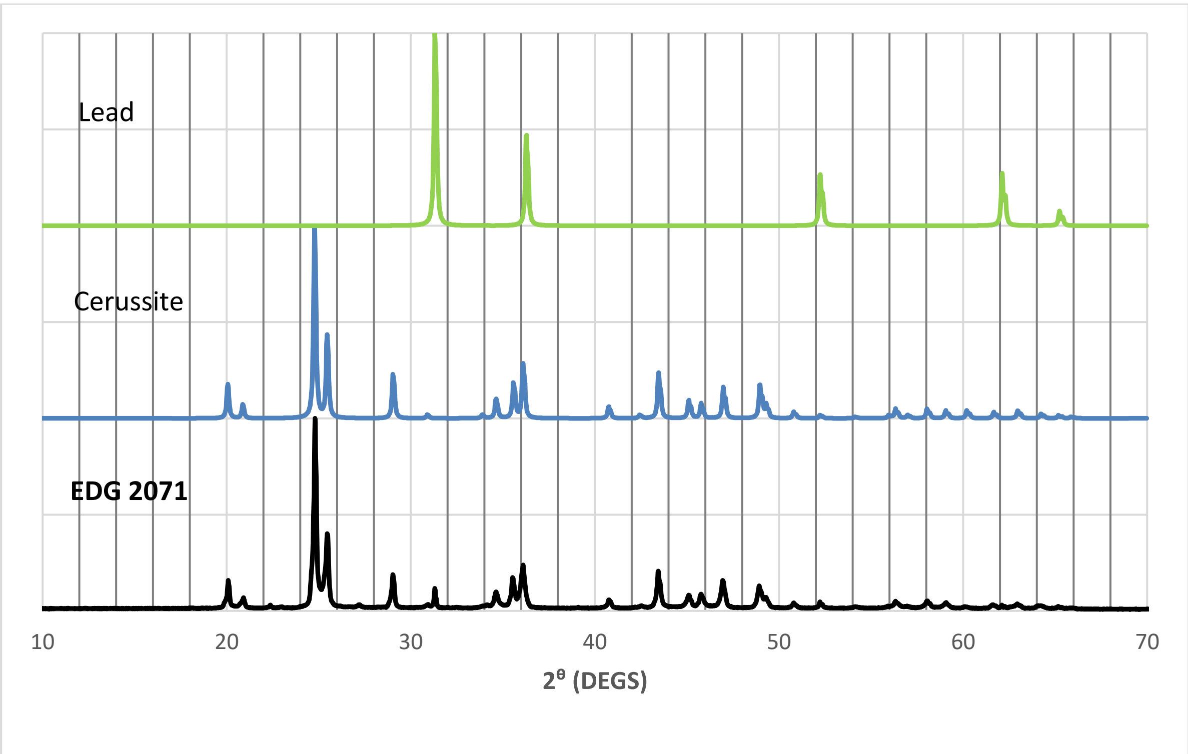


Figure 163: XRD spectra for bullet EDG 2071. The main compound present is cerussite with traces of metallic lead. This bullet contains 92% lead.

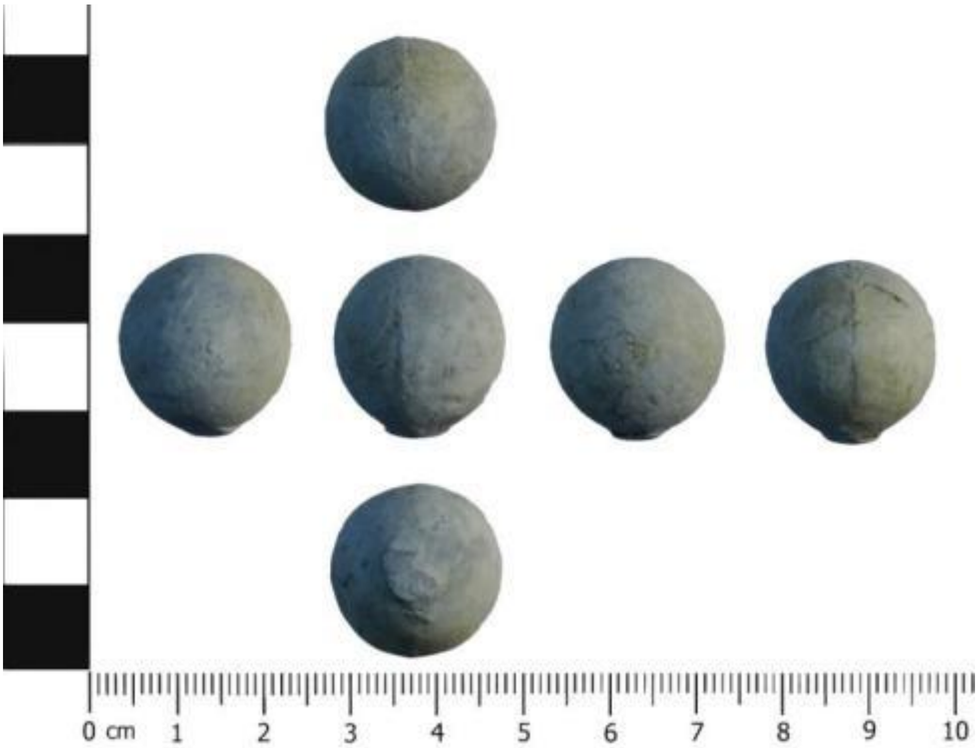


Figure 164: Bullet EDG 2071 with smooth stable patina. Condition 1, very good.

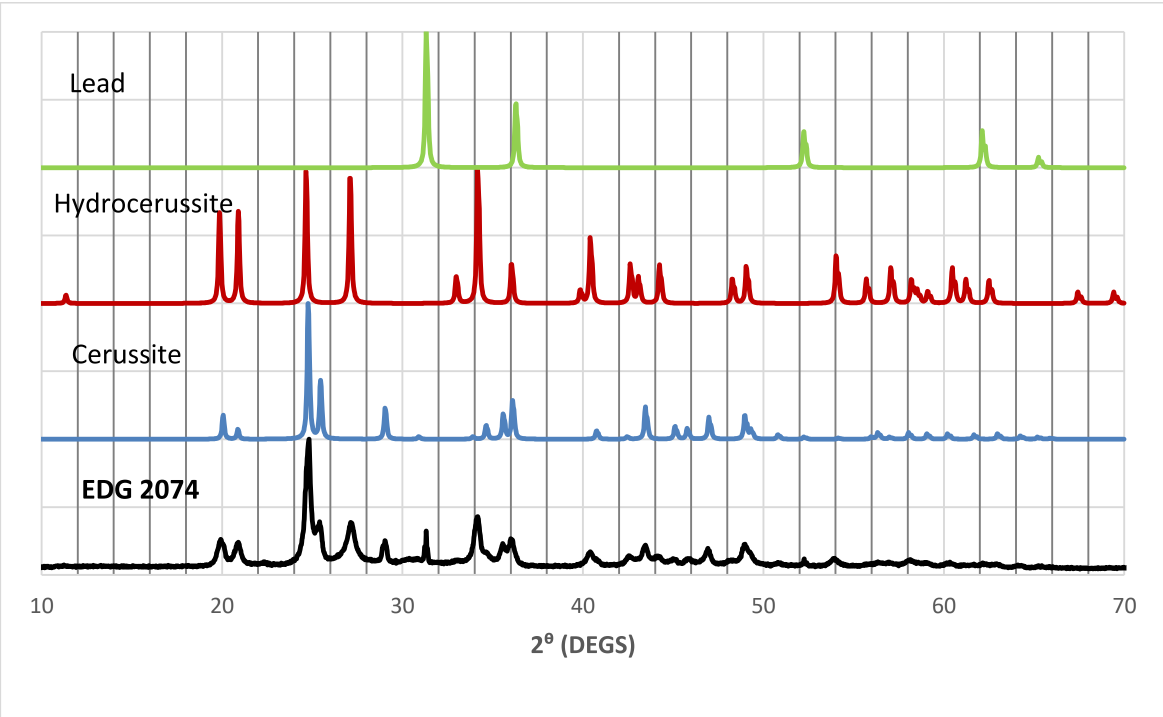


Figure 165: XRD spectra for bullet EDG 2074. The main compounds present are cerussite and hydrocerussite with a trace of metallic lead. This bullet contains 95.7% lead.

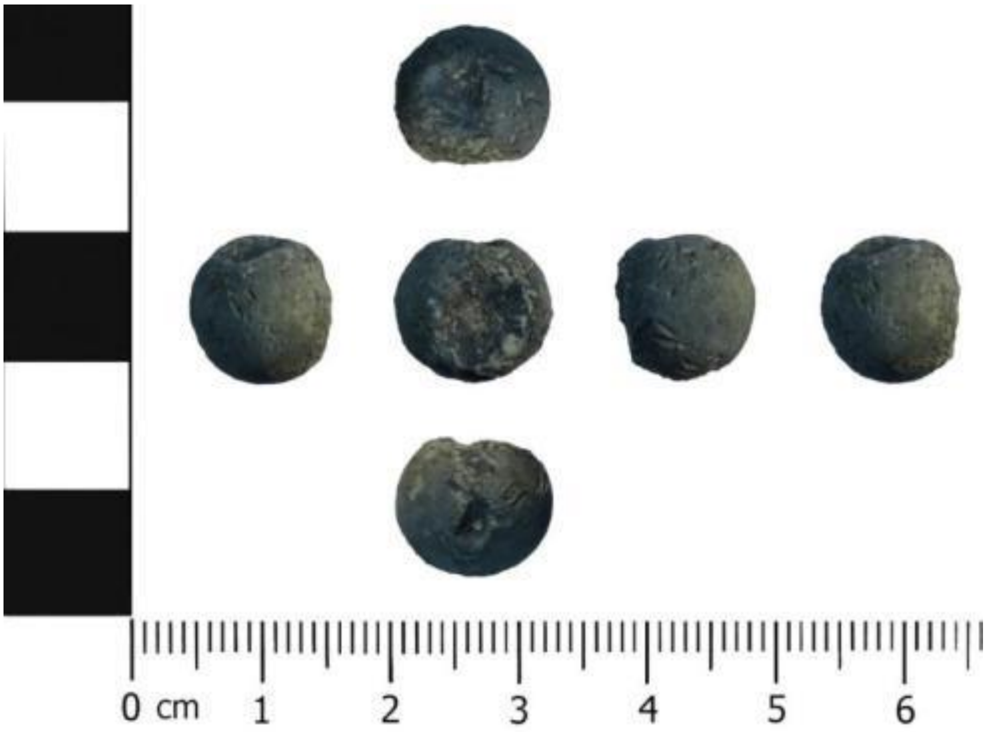


Figure 166: Bullet EDG 2074 with chewed marks but stable patina. Condition 2, good.

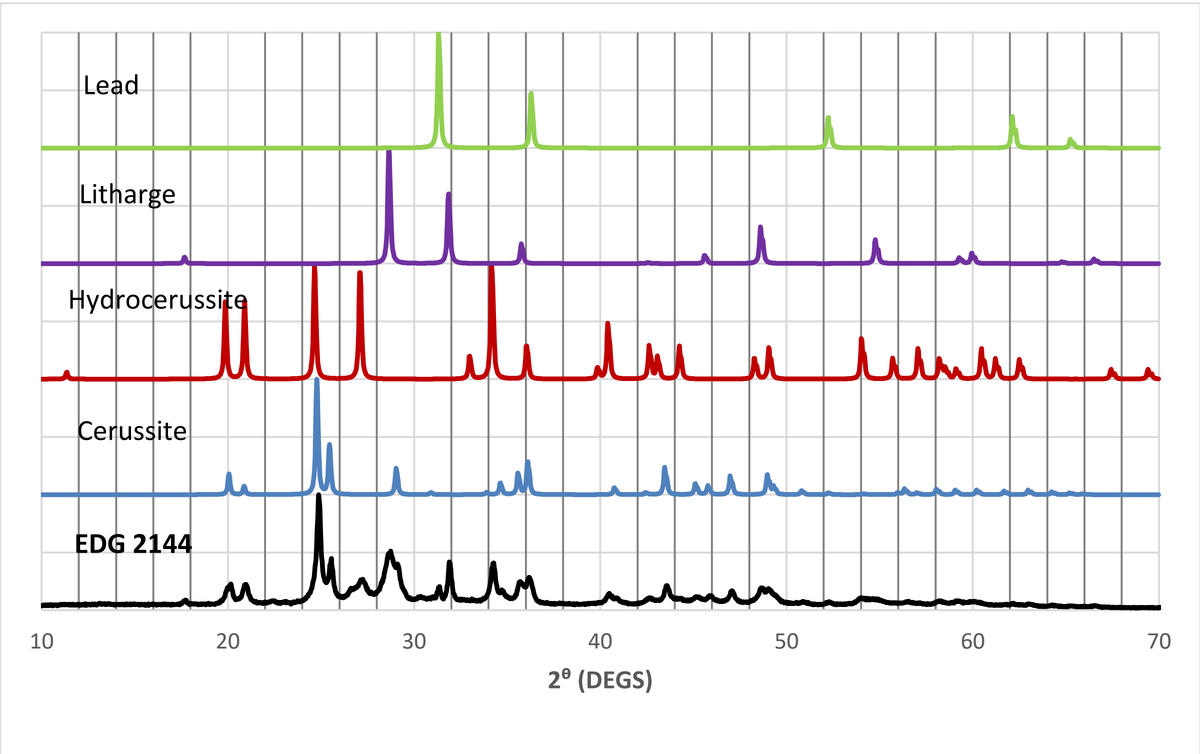


Figure 167: XRD spectra for bullet EDG 2144. The main compounds present are cerussite, litharge, hydrocerussite and metallic lead. This bullet contains 90% lead.

Figure 168: Bullet EDG 2144 with slight patina breakdown. Condition 2, good.

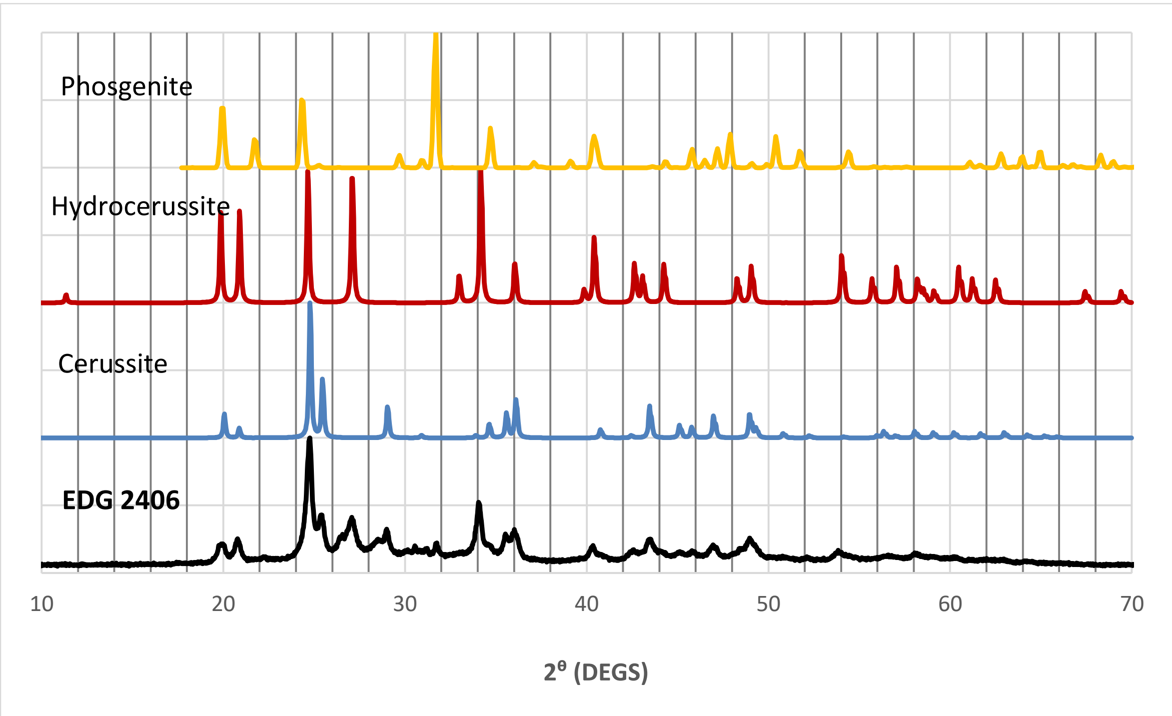


Figure 169: XRD spectra for bullet EDG 2406. The main compounds present are cerussite and hydrocerussite with a trace of phosgenite. This bullet contains 92.8% lead and 4.1% tin.

Figure 170: Bullet EDG 2406 with rough pitted surface and some patina breakdown. Condition 3, fair.

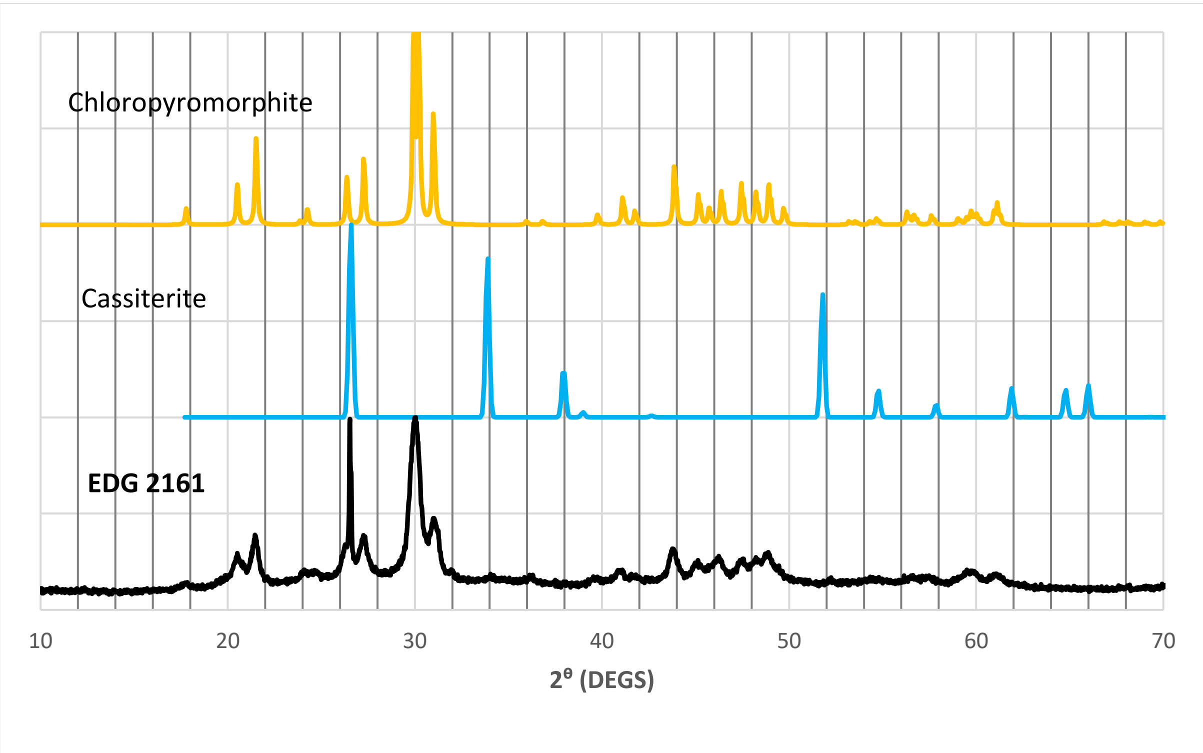


Figure 171: XRD spectra for bullet EDG 2161. The main compounds present are cassiterite and chloropyromorphite. This bullet contains 89% lead and 5.1% tin.

Figure 172: Bullet 2161 with smooth stable patina. Condition 1, very good.

6.7 Soil data and bullet condition analysis

Statistical analysis was carried out for each soil parameter against the condition of lead bullets. It should be noted that statistical significance is unlikely at this site due to the small range of condition scores recorded for the bullets. The best bullet scores a total of 5 and the worst from this site scores an 11 and are all in relatively good condition. Soil layers referred to and their depth are presented in table 58.

Soil context	Soil depth range	Soil depth average
Topsoil	0.15-0.40m	0.27m
Subsoil	0.30-1.10m	0.59m
Lower subsoil	0.50-1.2m	0.77m
Natural	0.75-1.15m	0.95m

Table 58: Recorded soil contexts and corresponding depths.

6.7.1 pH results

pH ranges from 4.86 to 7.89 $CaCl_2$ (5.40 to 8.79 H_2O) through the soil column, increasing with soil depth. As the box plot shows (figure 173), topsoils vary quite considerably from acidic to slightly alkaline, with an average pH of 6.91±0.72. This is similar to previous analysis carried out at the site which recorded the topsoil at pH 7.2 (Foard and Morris 2012, 151). Subsoils and lower deposits are consistently alkaline. Seven samples are lower than pH 6.5, the lowest of which is pH 4.86, which is very acidic compared to the rest of the site. In general the results show the site to be neutral to slightly alkaline with very little variation in pH levels in subsoils.

When the pH of the topsoil is mapped across the site, it is apparent that the majority of soils are between pH 7 and 8 (mapped in purple and black) (figure 174 and 175). This range is an ideal pH for the preservation of lead as it encourages the formation of solid stable patinas and does not promote the breakdown of lead compounds (Costa and Urban 2005, 50). The most acidic samples occur in fields D and F. Field F contains a very acidic sample of 4.86, sampled at a height of 76m AOD on a steep downhill slope. This field has been in cultivation since at least the early 1990s. It may be that the cultivation and addition of fertilisers to cereal crops has allowed the soil to develop greater acidity in this area. This sample also contained some of the highest levels of organic matter of the site, recorded at 11.05% which may have contributed to the level of acidity (Rowell 1994, 153).

However, the second most acidic sample of pH 5.72 occurs in Field D which is a long term pasture field with existing ridge and furrow and has not been cultivated since at least the 17th century. The organic content of this sample was also one of the highest from the site at 11.22%. However, the acidity in Field D does not match the acidity level of Field F which is at a level which in theory could cause severe damage to buried lead. These two pH readings do stand out from the rest of the site and may represent anomalies or temporary fluctuations in pH. Further extensive sampling of both fields would enable a pattern of pH to be established and to identify whether this acidity continues as a trend across both fields. All samples, bar the single acidic reading of 4.86, indicate that the pH of the site would not be expected to be particularly damaging to lead artefact preservation. As discussed in section 2.1.3, anything below pH 5.5 will increase the potential for passive patina layers to dissolve from metal surfaces.

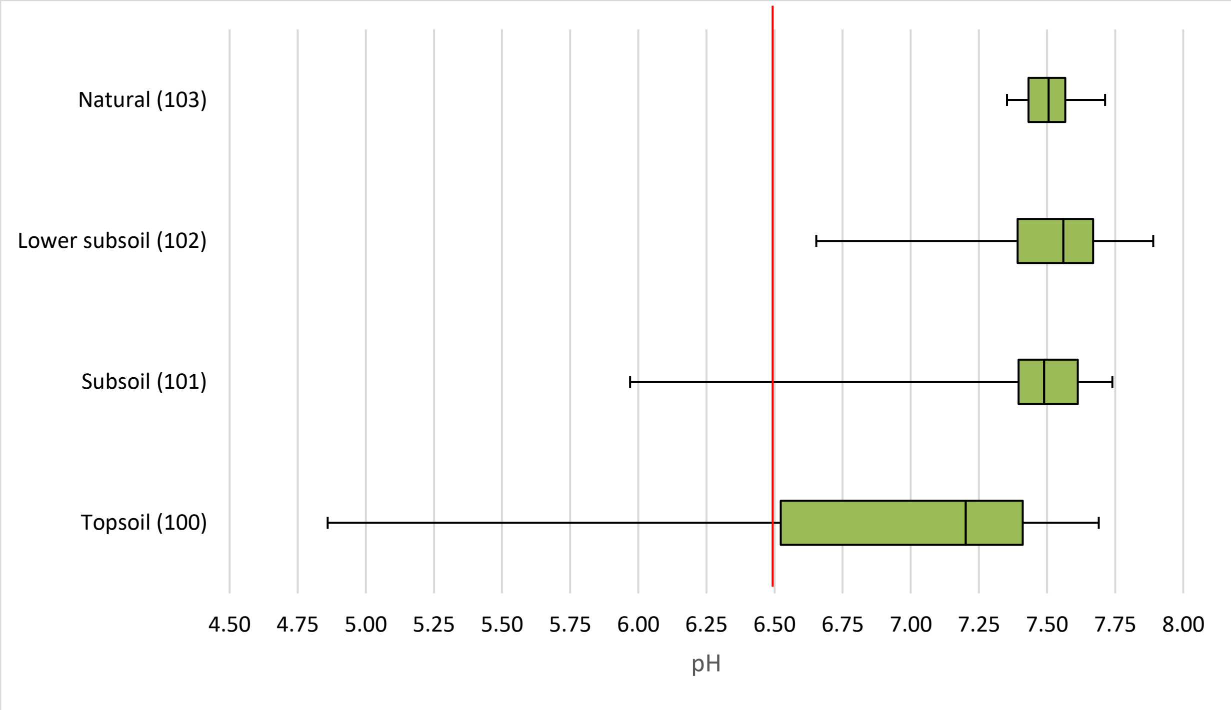


Figure 173: Box plots showing pH range of all soils from each context with pH changing little in deposits deeper than the topsoil. The red line indicates a neutral soil pH.

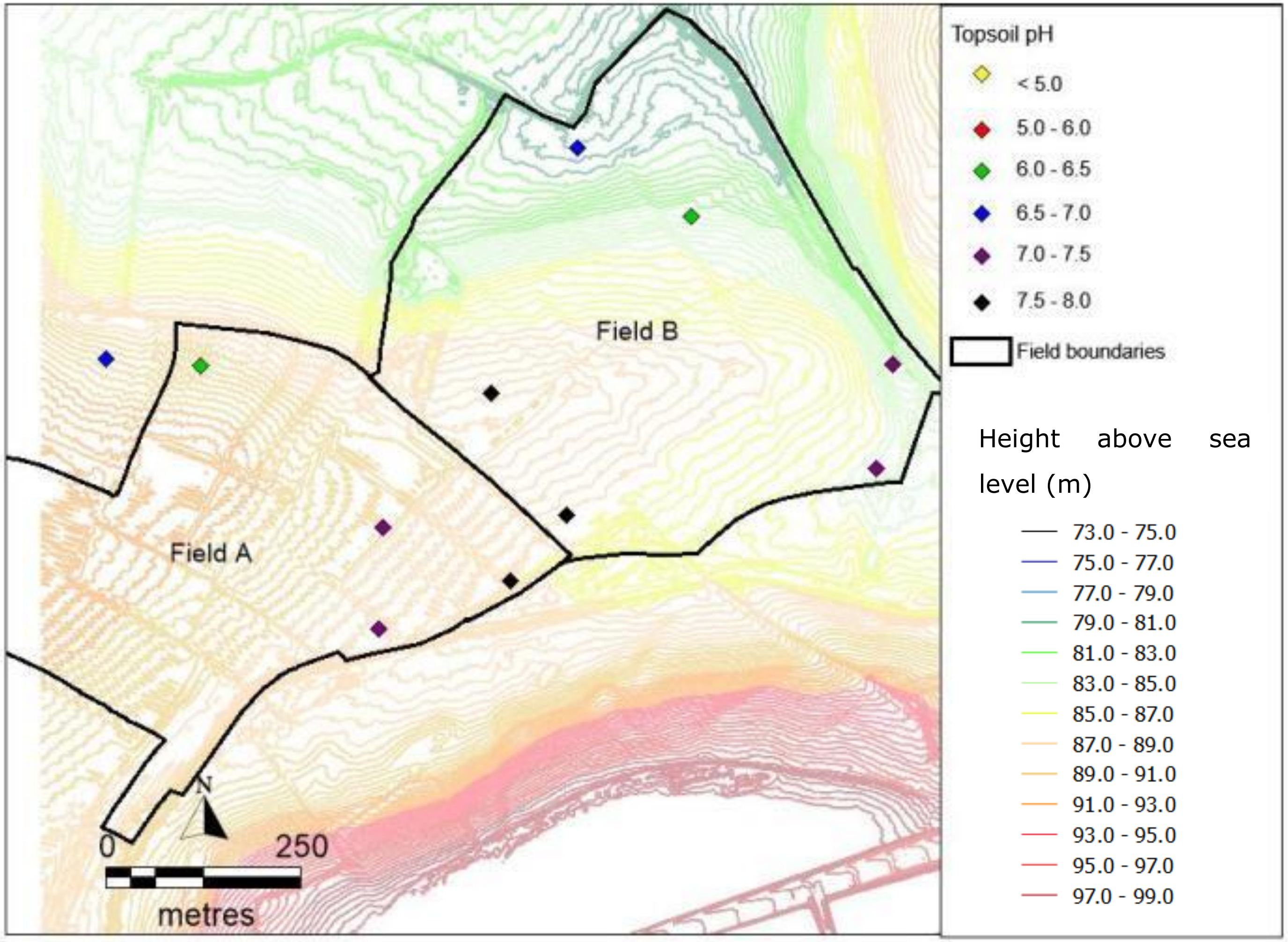


Figure 174: Distribution of pH levels in topsoil samples across fields A and B, highlighting areas of acidity and alkalinity against topography. Samples are consistently recorded as neutral to alkaline. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

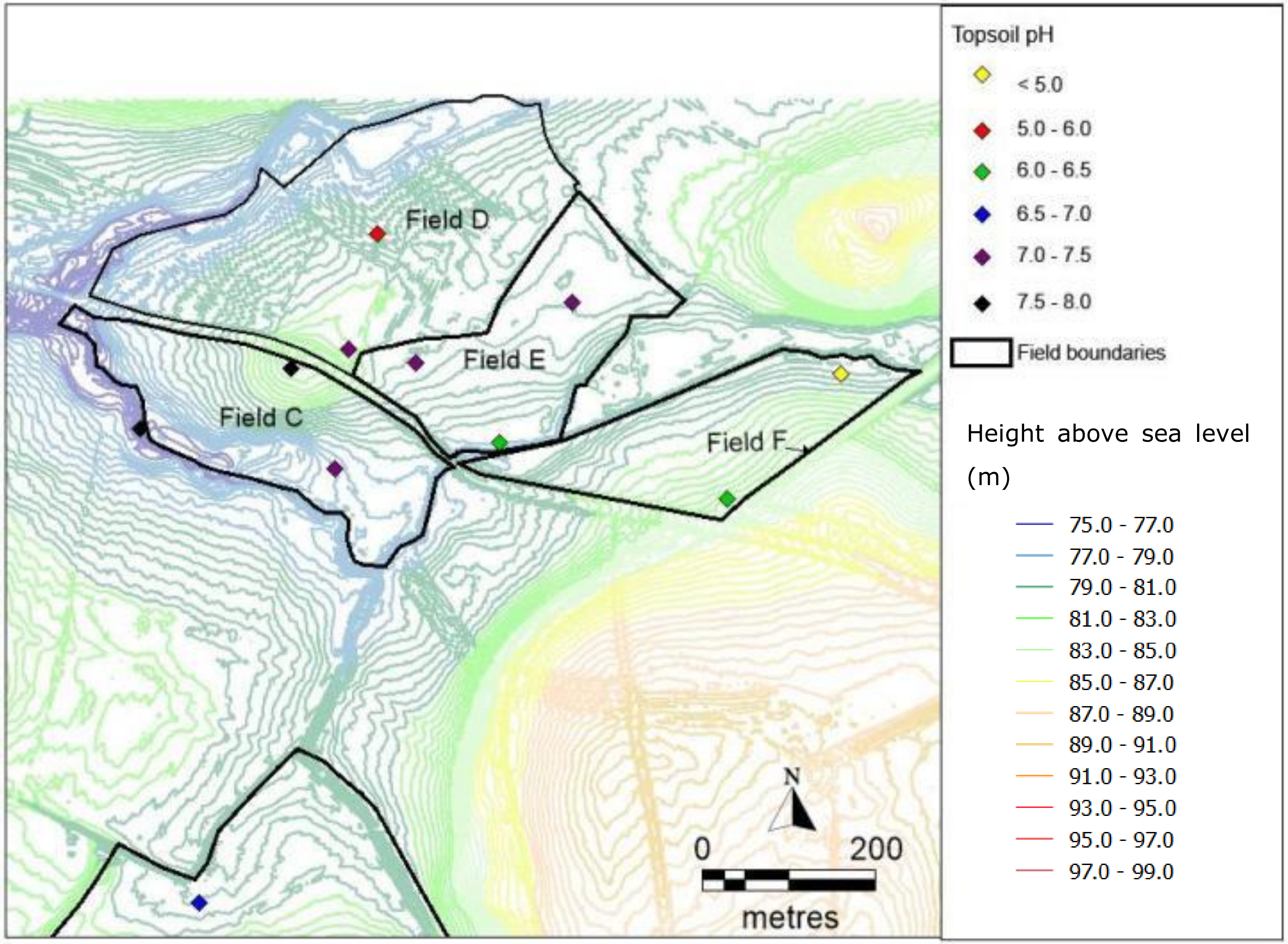


Figure 175: Distribution of pH levels in topsoil samples across fields C, D, E and F, highlighting areas of acidity and alkalinity against topography. The acidic reading of 4.86 is highlighted in yellow. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

6.7.1.1 pH levels against bullet condition

When the condition of each bullet is plotted against the pH of the soil at Edgehill, no trend can be seen (figure 176). As discussed above, the neutral to alkaline conditions on the site would not pose a threat to the integrity of lead artefacts. Even though two bullets have been retrieved near acidic conditions of 4.86, their condition has not been jeopardised and they still only score a total of 7 out of a possible 20 in the five category condition assessment. This distinct lack of correlation between pH and the condition of bullets is represented by a correlation coefficient of 0.003, signifying no statistical significance (table 59).

It appears that even acidic levels on the site have not allowed bullets to deteriorate in condition. However, the sample of bullets retrieved from this area is very small. Nonetheless, it appears other factors must play a role in the preservation of bullets at the site.

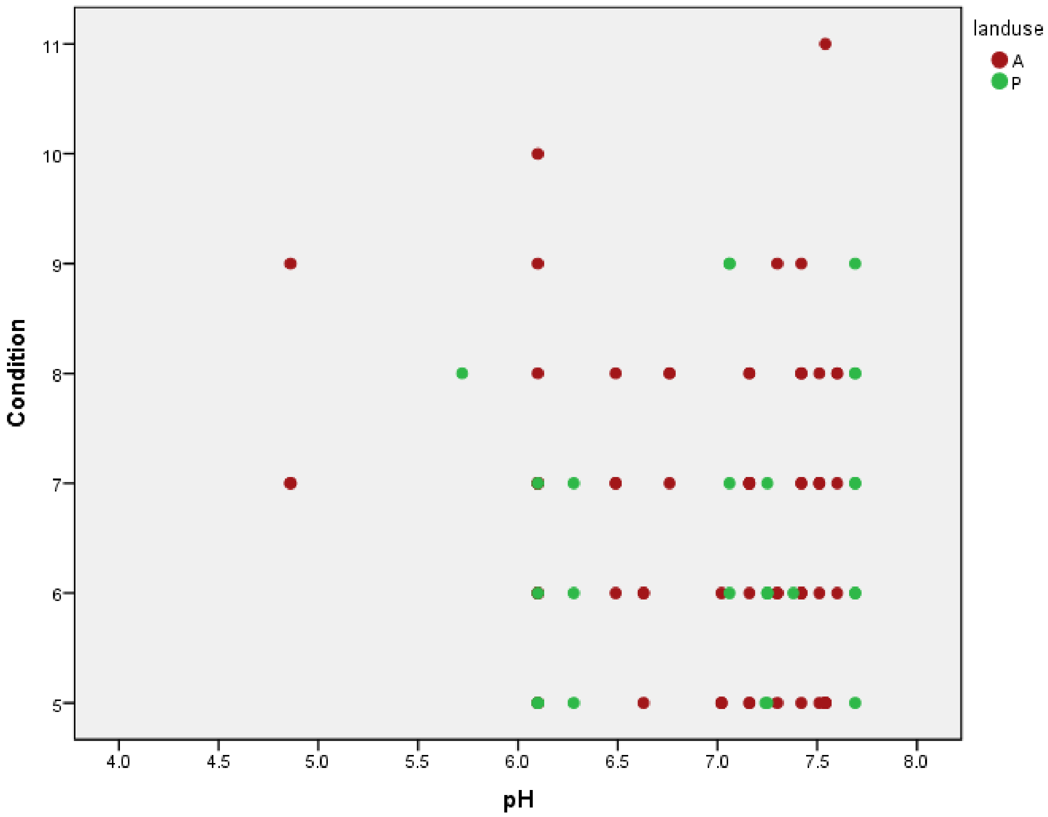


Figure 176: Scatter plot showing the pH of the soil against the condition of bullets, showing no trend. (A= arable, P= pasture).

			Condition	pH
Spearman's rho	Condition	Correlation Coefficient	1.000	.003
		Sig. (2-tailed)	.	.978
		N	95	95
	pH	Correlation Coefficient	.003	1.000
		Sig. (2-tailed)	.978	.
		N	95	95

Table 59: Spearman's rank correlation coefficient of 0.003 for condition of bullets against soil pH which is not significant.

6.7.2 Conductivity results

Conductivity ranges from 24.73 to 427.67µS/cm across the site (figure 177), and generally decreases with soil depth. Average levels in topsoils are 127.14±97.04µS/cm, for subsoils average levels are 71.50±17.71µS/cm, lower subsoils 80.70±15.75µS/cm, and natural deposits 119.64±49.70µS/cm. Range of conductivity is significantly higher in topsoil deposits, with lower ranges further down the soil column (figure 178). Though levels do decrease with soil depth, natural deposits start to increase again at depths greater than 0.75m, indicating that the soil column is retaining its conductivity, probably due to the reactive surface of the clay particles forming the colloidal fraction in the soil (see section 2.3.3.3).

The average conductivity of the topsoil measures 127.14µS/cm which is not particularly high and although would enable corrosion to take place, would not be deemed as particularly aggressive (see section 2.2.10). However, in some areas the topsoil conductivity does reach 427.67µS/cm which is relatively high and may promote corrosion in metals. Studies have shown that conductivity above 200µS/cm could lead to an aggressive soil environment (Corcoran *et al.* 1977)).

When conductivity is mapped using ranges it is evident that the lowest levels of conductivity reside in areas of long term pasture (figure 179). Levels of 100µS/cm and above are consistently recorded in fields B and C which have been under cultivation since at least the early 1990s. Higher levels of conductivity also occur at lower levels down slope in fields B, C and F. The higher levels of conductivity in these areas are likely to be related to the water content of the soil, the regular cultivation of fields which will aerate soil and improve water flow through the particles, and the annual use of fertilisers introducing salts to the soil.

The water content of samples can be correlated with the conductivity across the site and it is revealed that conductivity increases with water content, with a coefficient value of 0.239 which is statistically significant (figure 180 and table 60). This is what would be expected as higher water contents give a greater amount of solution for salts to conduct and so conductivity levels will rise accordingly. The highest conductivity reading in long term pasture is recorded at 85.45µS/cm, which is no doubt due to a lack of cultivation.

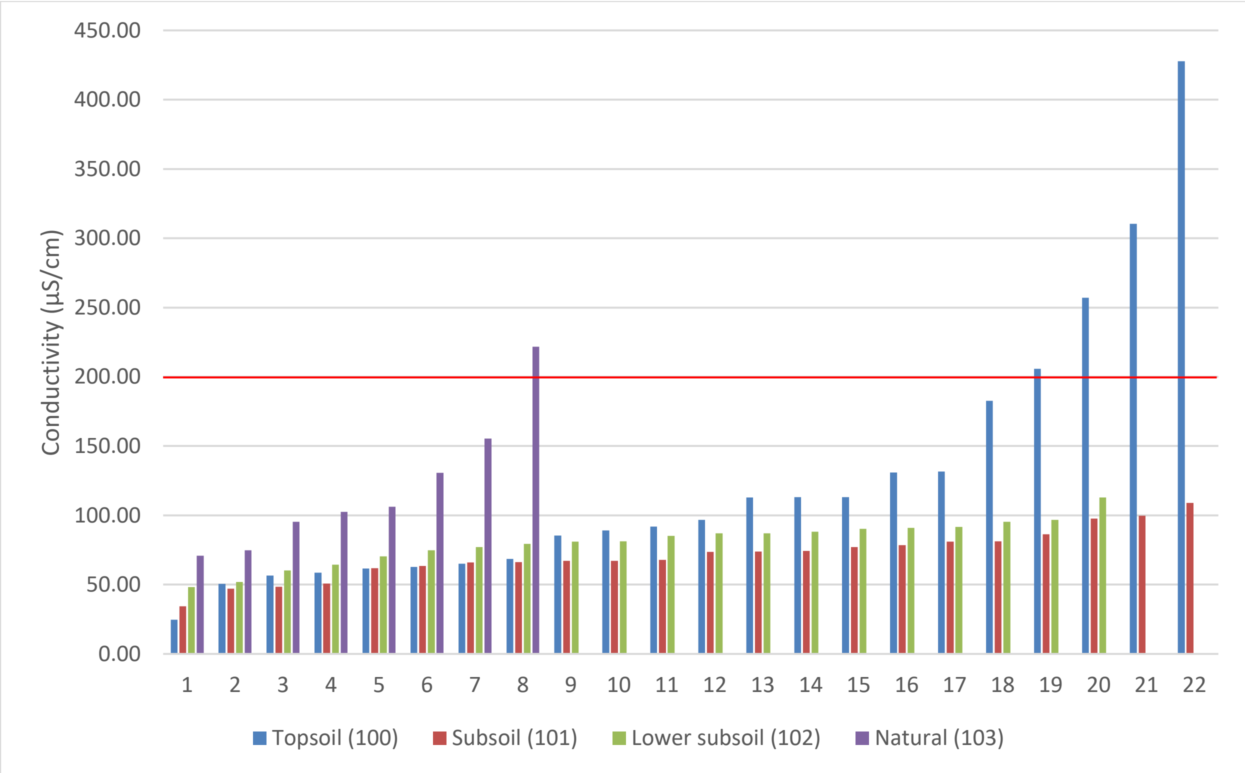


Figure 177: Results of all conductivity measurements taken at the site in ascending order. Above the red line represents potentially aggressive soil conditions.

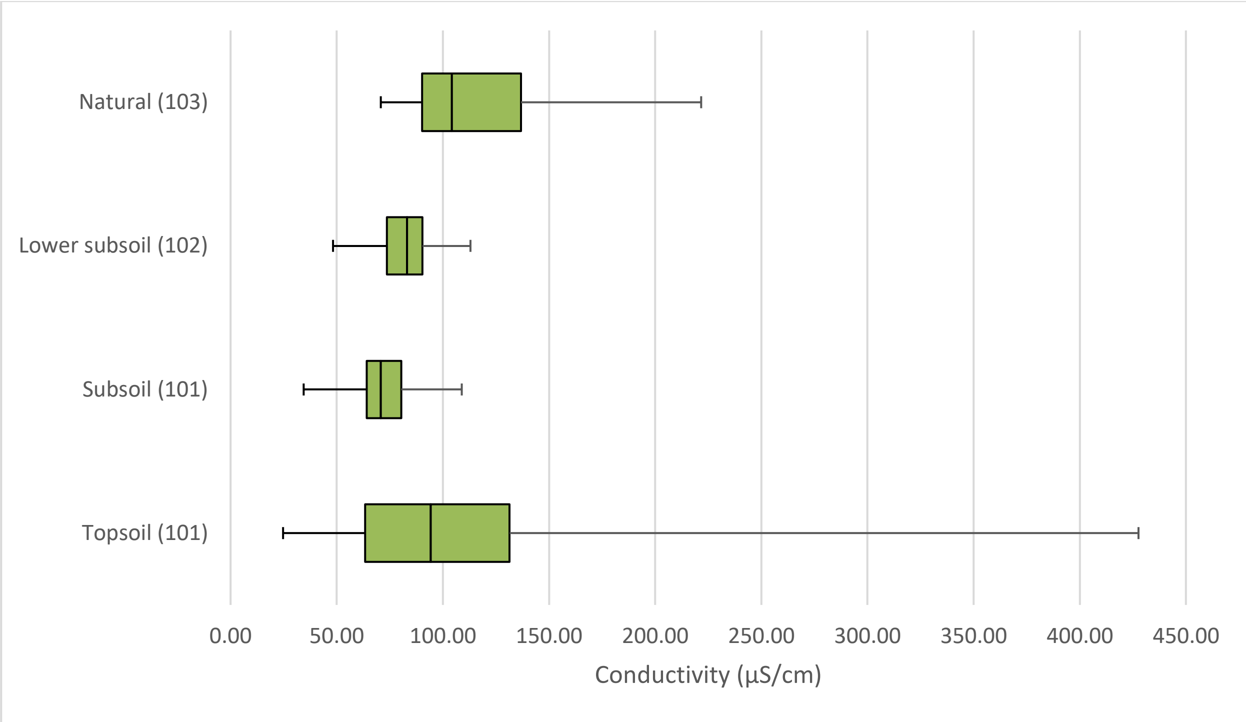


Figure 178: Box plots showing conductivity range of all soils from each context highlighting the range in topsoil levels.

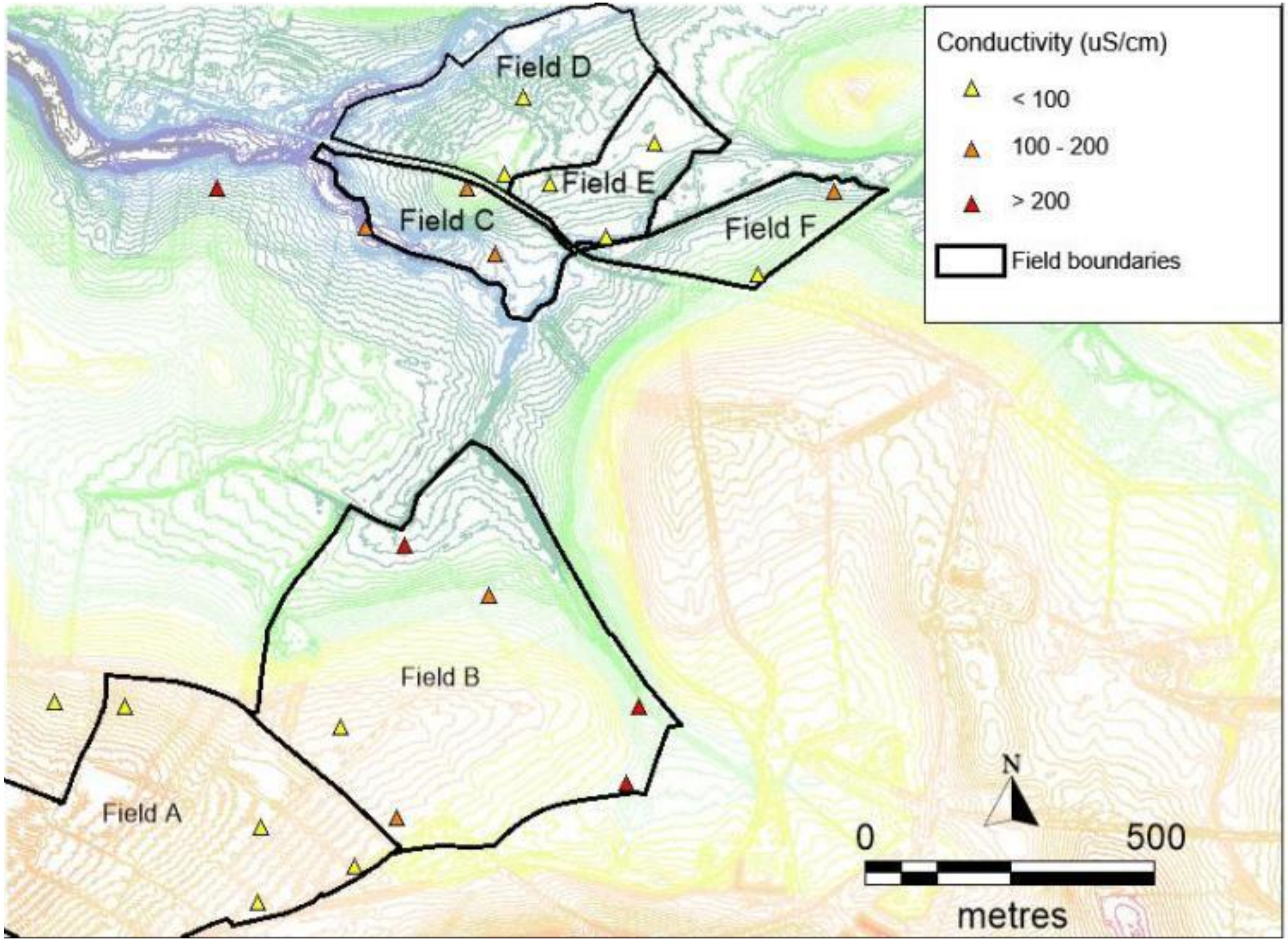


Figure 179: Distribution of conductivity levels in topsoil samples across the site, highlighting areas of low and high conductivity. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

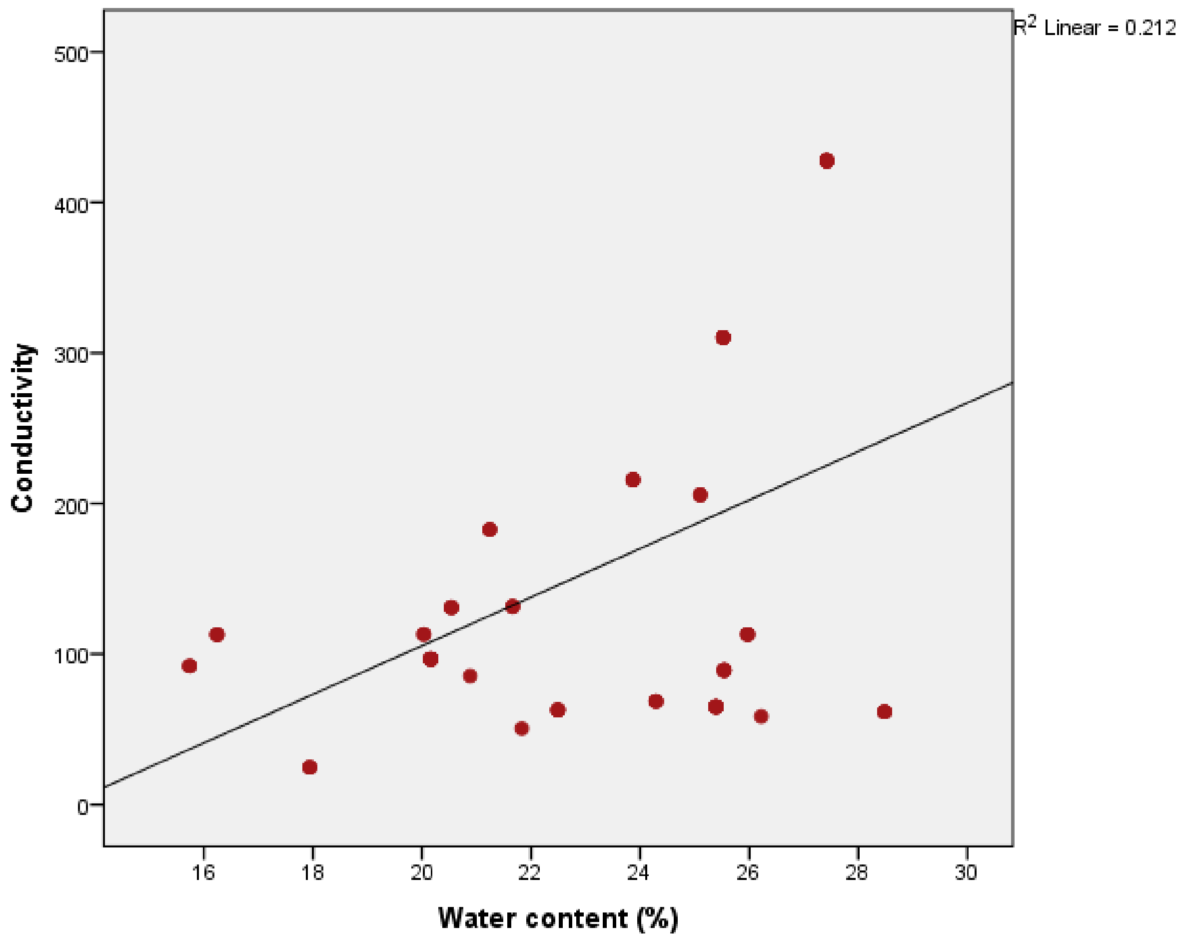


Figure 180: Scatter plot showing a positive correlation between water content and conductivity of the soil at Edgehill. As a slight trend, as water content of the topsoil increases, the conductivity level also increases.

			Water	Conductivity
Spearman's rho	Water	Correlation Coefficient	1.000	.239*
		Sig. (2-tailed)	.	.020
		N	95	95
	Conductivity	Correlation Coefficient	.239*	1.000
		Sig. (2-tailed)	.020	.
		N	95	95

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

Table 60: Spearman's rank correlation coefficient value of 0.239 between water content and conductivity which is statistically significant.

6.7.2.1 Conductivity levels against bullet condition

As discussed above, some conductivity readings from the site were deemed high enough to be classified as aggressive towards metals. However, when the conductivity is plotted against the condition of the bullets, no correlation is evident (figure 181). This is supported by the coefficient value of 0.094 which is very close to 0 indicating no significant correlation (table 61). However, it is interesting that the plot shows all the lowest conductivity readings to be present in long term pasture fields, with a much greater range of conductivity levels present in arable fields. All the pasture fields consistently have conductivity readings lower than 100µS/cm which also corresponds with lower readings of chloride and nitrate levels on pasture fields. This is probably due to cultivation increasing oxygen and water flow through the soil column allowing greater conductivity levels to develop. This could have an impact on future preservation of archaeological material on the site as high conductivity and salt content usually promotes corrosion. Keeping fields under pasture use may help the preservation of materials in the long term. As discussed below (section 6.8), It is evident that bullet condition is better in permanent pasture fields than in arable at Edgehill.

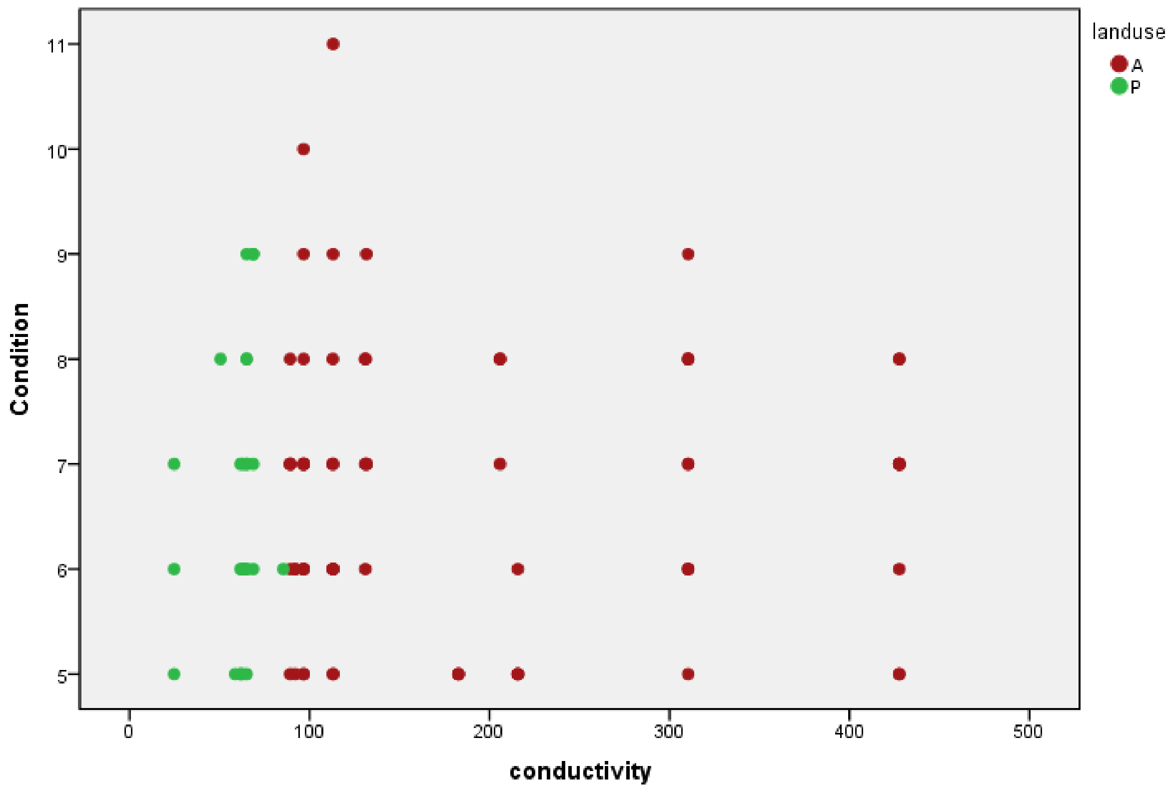


Figure 181: Scatter plot showing conductivity against the condition of bullets, showing no clear trend. Pasture is highlighted (in green) as being at lower conductivity levels than arable fields.

			Condition	Conductivity
Spearman's rho	Condition	Correlation Coefficient	1.000	.094
		Sig. (2-tailed)	.	.365
		N	95	95
	Conductivity	Correlation Coefficient	.094	1.000
		Sig. (2-tailed)	.365	.
		N	95	95

Table 61: Spearman's rank correlation coefficient of 0.094 for soil conductivity against the condition of bullets which is not statistically significant.

6.7.3 Water content results

Water content across the site ranges from 6.36% to 28.48% (figure 182), with water content declining with soil depth. Any content above 20% should be deemed an aggressive soil which means the majority of the topsoil has enough water content to be deemed aggressive, with an average water content of 22.66±0.03% (Corcoran *et al.* 1977; Booth *et al.* 1967). Water content at the site is on average higher than at both Moreton Corbet and Wareham. The higher water content is associated with the clay content of the soil. Clay particles have a larger surface area and have a closely packed structure resulting in a higher water-holding capacity.

When the water content of the soil is mapped, it is apparent that water content tends to be higher in lower lying areas of the site, particularly in the northern fields D, E, and F where the site resides at a lower topography (figure 183). This pattern of water content with topography on the site was also observed at Moreton Corbet, with higher water levels in down slope areas of the site.

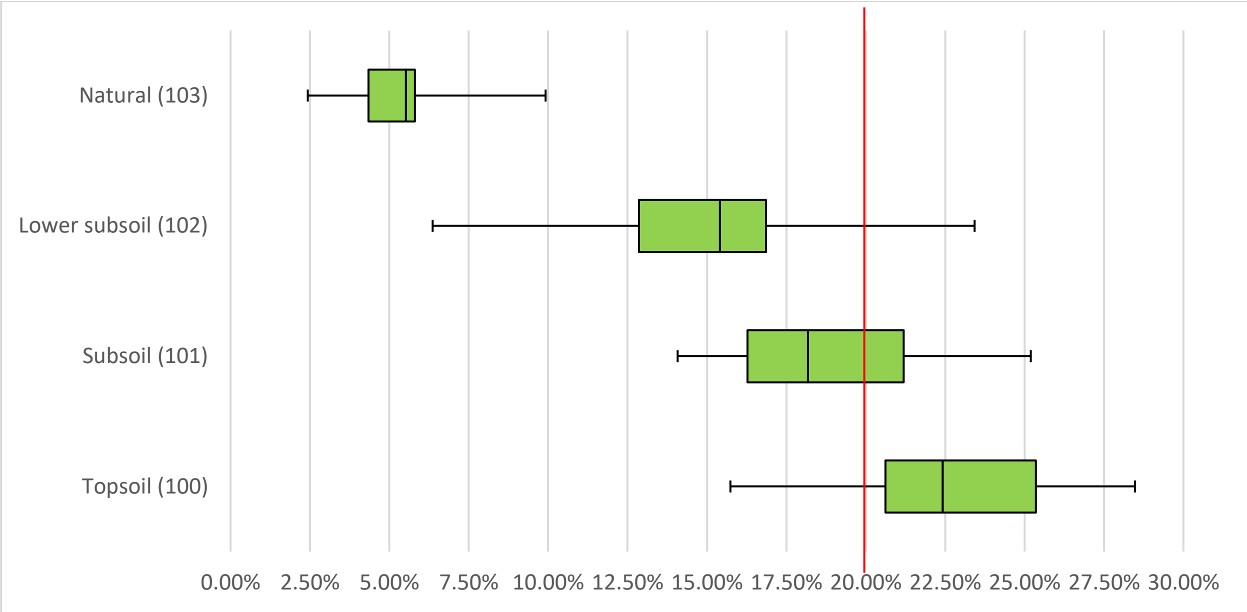


Figure 182: Box plot showing water content range of all soils from each context. The red line indicates when water levels should be deemed potentially aggressive.

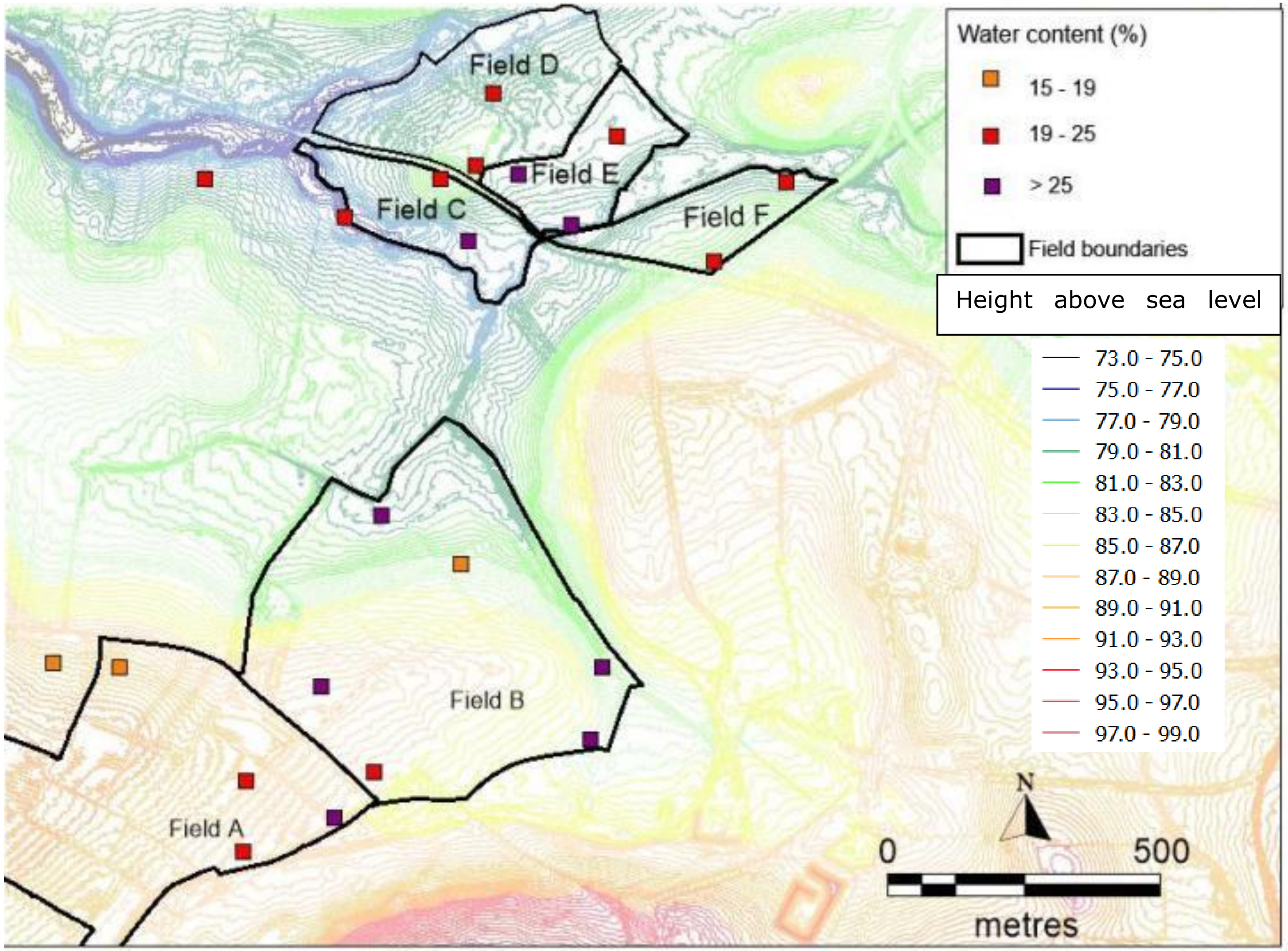


Figure 183: Distribution of water content in topsoil samples across the site, highlighting lower water levels upslope and higher water levels down slope. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

6.7.3.1 Water content against bullet condition

The majority of the soil samples from Edgehill contained enough water to be deemed an aggressive level which could promote the deterioration of metals. However, when the condition data is plotted against the water content in the soil, no correlation is present (figure 184). Spearman's correlation coefficient value is 0.000 meaning no correlation exists on this site between water content and the condition of bullets (table 62). It suggests water levels are not high enough to cause significant damage to the bullets. Land use also does not seem to have an effect on the water content of the soil, with relatively high contents in both arable and pasture fields. However, this lack of correlation is also due to the lack of variation in bullet condition scores from across the site.

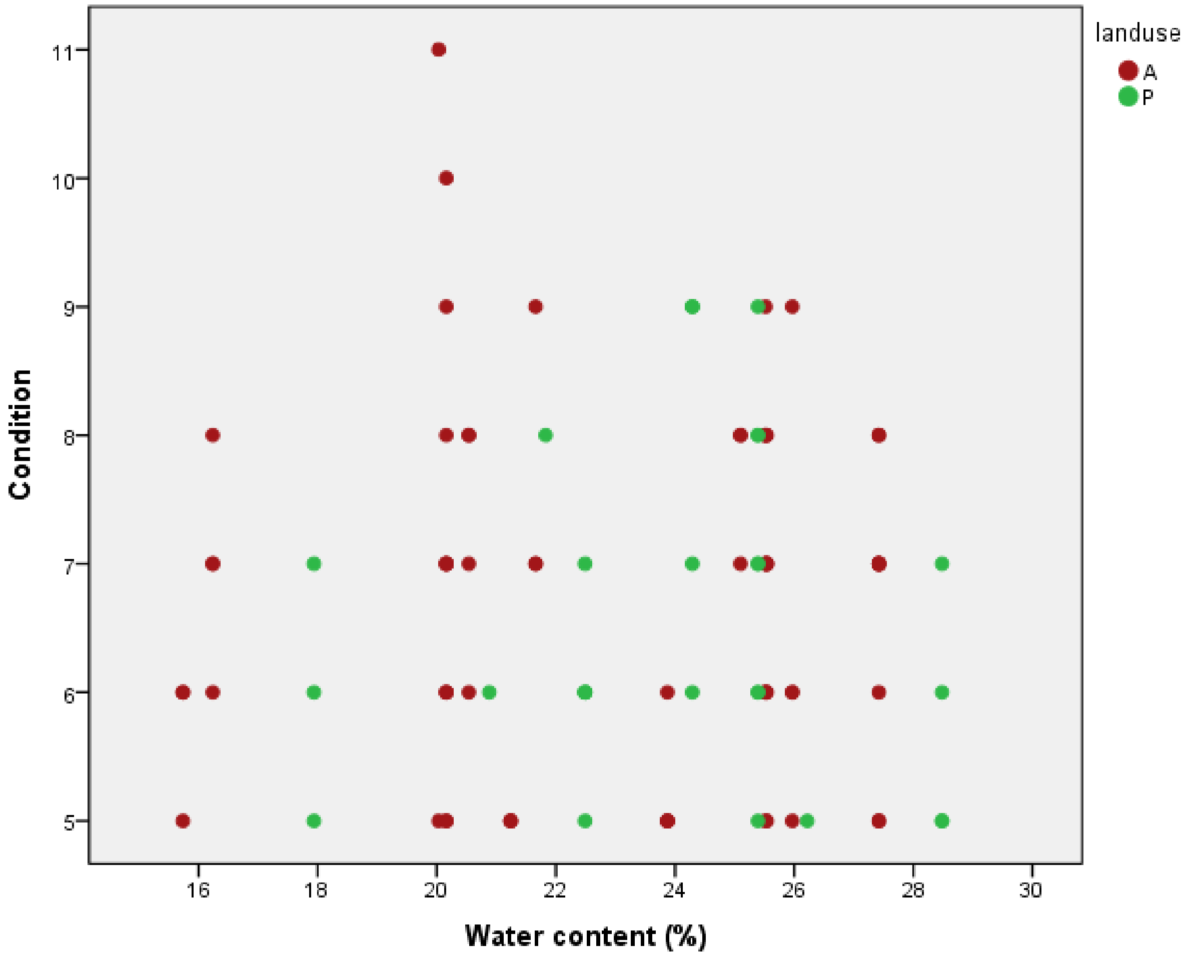


Figure 184: Scatter plot showing water content of soil against the condition of bullets, showing no relationship.

			Condition	Water
Spearman's rho	Condition	Correlation Coefficient	1.000	.000
		Sig. (2-tailed)	.	.997
		N	95	95
	Water	Correlation Coefficient	.000	1.000
		Sig. (2-tailed)	.997	.
		N	95	95

Table 62: Spearman's rank correlation coefficient of 0.000 for water content of soil against the condition of bullets. No relationship is present.

6.7.4 Organic content results

Organic content ranges from 2.22% to 12.95% across the site (figure 185). Highest organic levels are found in the topsoils, with all levels above 10% organic content found in topsoil contexts (figure 186). A soil with 10-20% organic matter can be classed as an 'organic soil' and over half the samples from the topsoil were recorded as over 10%. To be an aggressive soil organic content should be over 20% so these levels of organic matter content are not particularly aggressive levels though do have reasonable organic matter content (see section 2.3.3.7).

When the organic content of topsoil is mapped across the landscape, it is evident that levels of 12% and above almost exclusively reside in Field A which is a long term pasture field (figure 187). Field A has not been ploughed since at least the 17th century and has therefore not seen its organic content removed by the regular planting and ploughing of new crops. In general, lower organic content is found in fields that have been cultivated since at least the early 1990s as they have seen their organic content removed and replaced over decades of cultivation episodes.

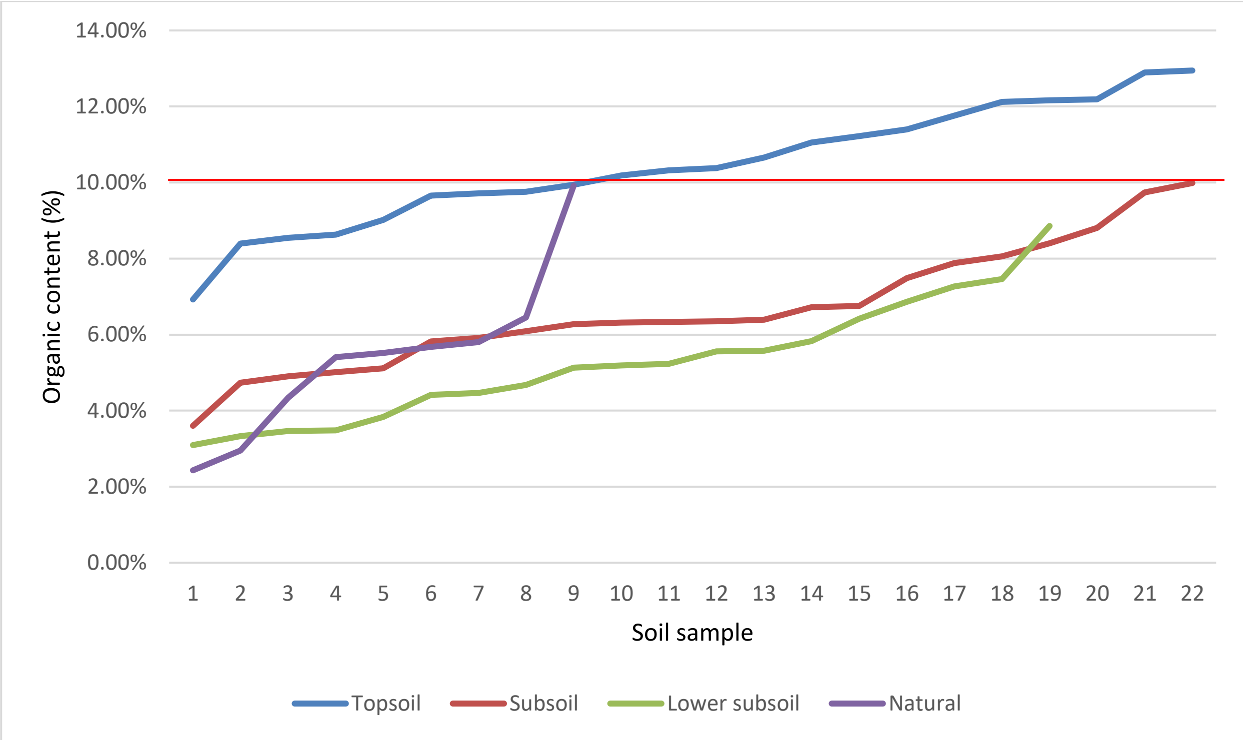


Figure 185: Results of all organic content measurements taken at the site in ascending order. The red line indicates when soils can be referred to as 'organic'.

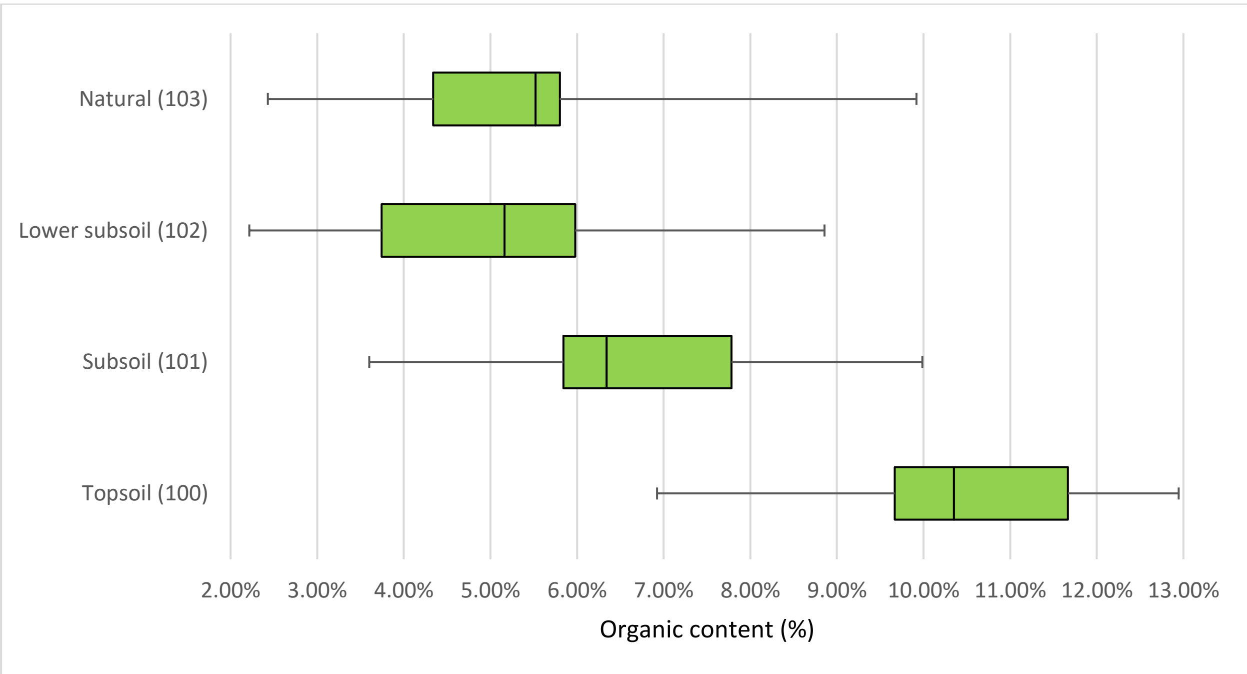


Figure 186: Box plot showing organic content range of all soils from each context.

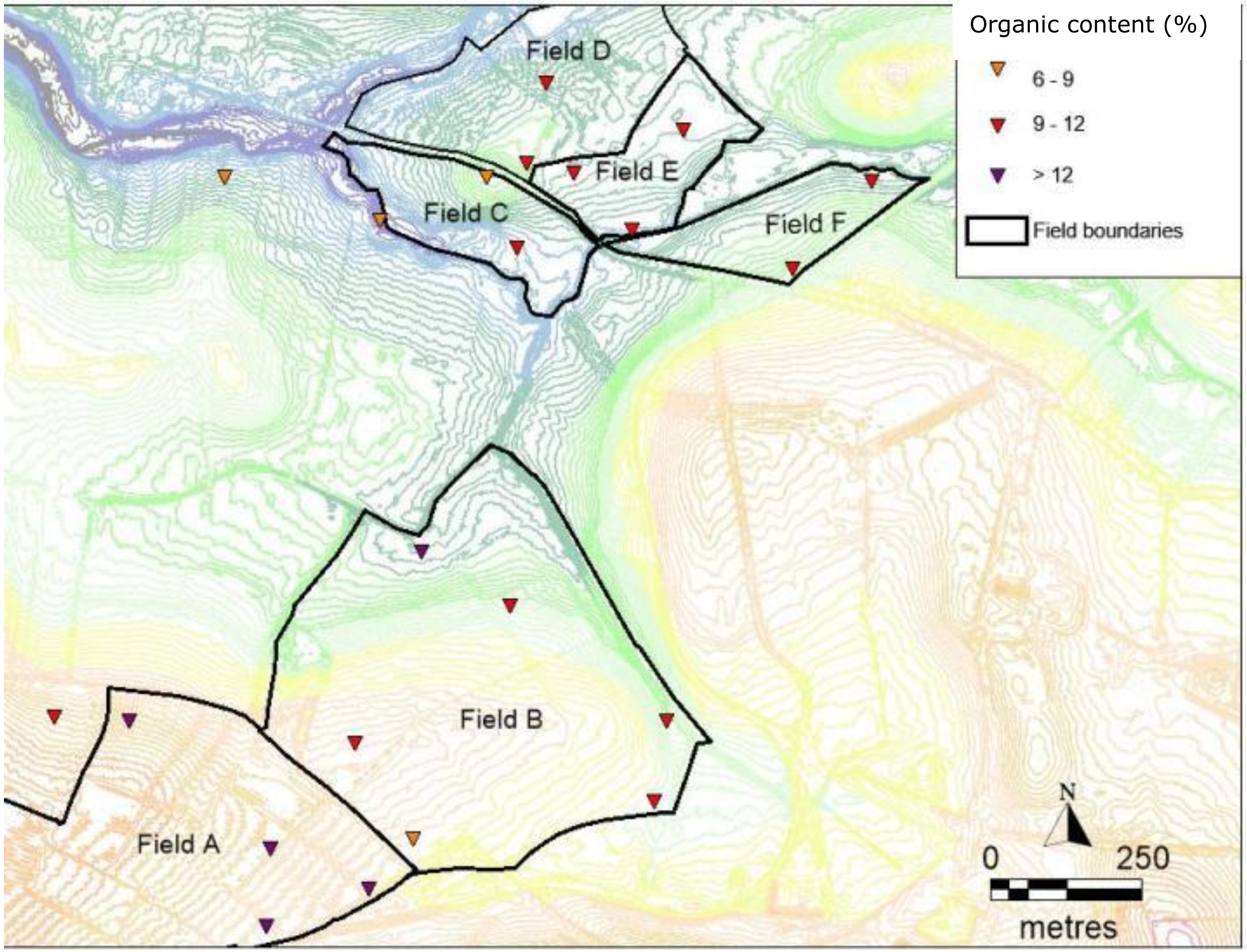


Figure 187: Distribution of organic content of topsoils across the site. Higher contents above 12% occur almost exclusively in Field A which is an area of long term pasture. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

6.7.4.1 Organic content against bullet condition

When the soil organic content is plotted against the condition of lead bullets, there is a very slight positive correlation with condition score increasing with organic content, though this is a very slight trend (figure 188). The coefficient for this relationship has a value of 0.181 (table 63) which is not statistically significant, but is the strongest relationship so far of the soil parameters. The chart shows interestingly that the highest organic contents occur in pasture fields on the site. Studies have shown that reversion from arable to pasture results in a rapid recovery of soil organic matter due to input from grass roots and a lack of physical disturbances from the soil such as ploughing (Romkems, van der Plincht, and Hassink 1999). However, this higher level of organic content in pasture fields has no negative effect on the preservation of artefacts as bullets are shown to be better preserved in pasture than arable fields.

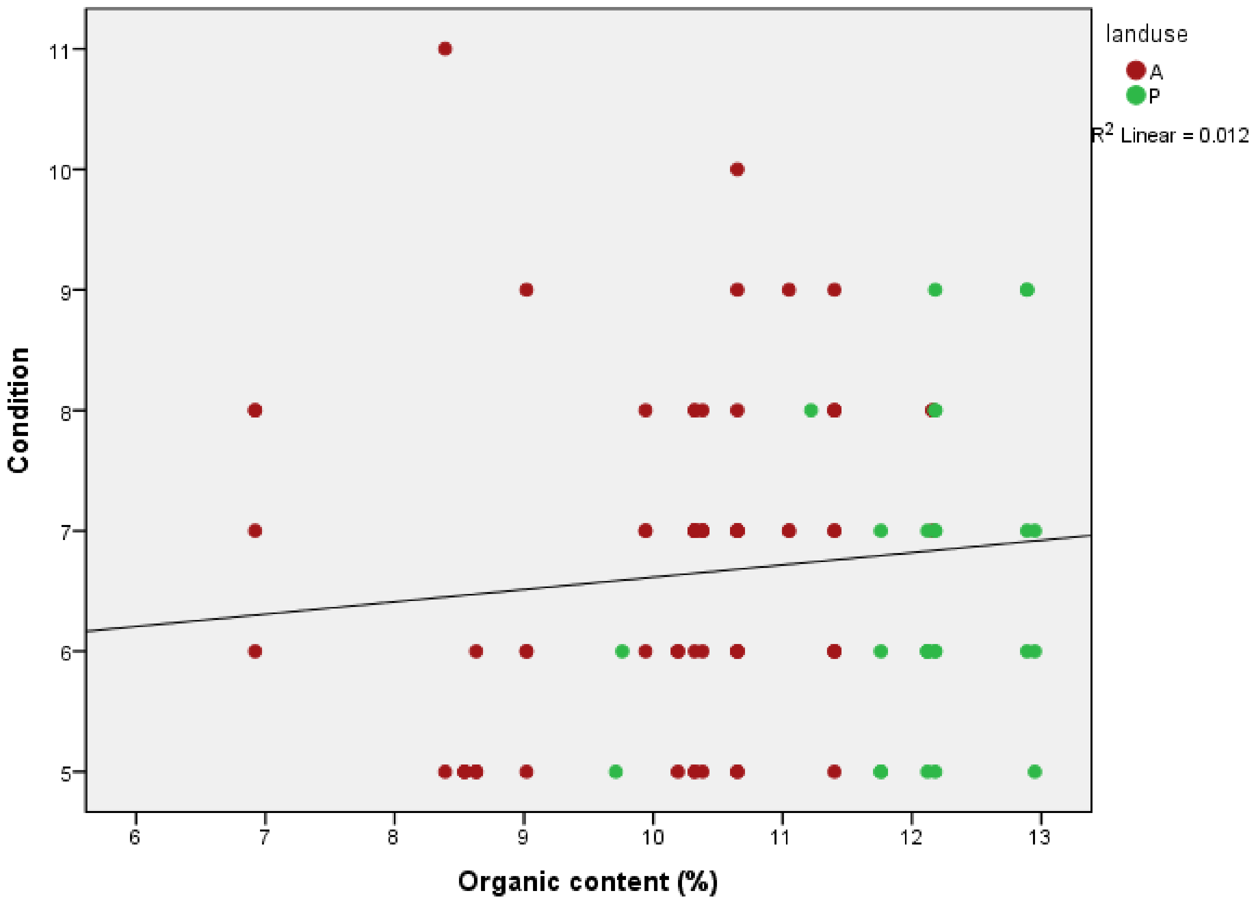


Figure 188: Scatter plot showing the organic content of soil against the condition of bullets, showing no clear trend. Areas of higher organic content appear in pasture fields. (A= arable, P= pasture).

			Condition	Organic
Spearman's rho	Condition	Correlation Coefficient	1.000	.181
		Sig. (2-tailed)	.	.079
		N	95	95
	Organic	Correlation Coefficient	.181	1.000
		Sig. (2-tailed)	.079	.
		N	95	95

Table 63: Spearman's rank correlation coefficient of 0.181 for soil organic matter content against bullet condition. The correlation is not statistically significant.

6.7.5 Texture results

All soil samples were assessed in the field for texture, recorded as sandy clay, silty clay, or clay. Full sample profiles from seven of the 22 test pits were also tested using the Malvern Mastersizer 2000. It was deemed unnecessary to re-test every soil sample as the variation in texture appeared minimal, especially compared to the heterogeneous textures of the Moreton Corbet samples. A total of 20 soil samples were run on the Malvern Mastersizer, the results of which are shown in figure 189. 40% of the samples were clays, 30% clay loams, 25% silty clays, and 5% silty clay loams (figure 190). All topsoils were recorded as clays or clay loams indicating little variation in soil texture. Though texture class is restricted to three main classes (clay loam, silty clay, clay) clay content varies from 24.28% to 60.77%, and sand content varies from 2.76% to 38.74%. As sand content is always less than 40% no samples have a significant sand content.

The dominance of clay in the soil column suggests the site will be prone to restricted drainage and oxygen flow due to the small size of the soil particles (Gerwin and Baumhauer 2000; Caple 2004). This could have a significant impact on interaction with metals in the soil as a depletion of oxygen may result in a reduced ability for corrosion to take place and hence promote the preservation of metals.

The soil at Edgehill is predominantly alkaline. Consequently, the negatively charged anions and salts will not be retained by the negatively charged clay particles within the soil. This suggests that metal corrosion will be reduced as damaging anions such as nitrates, sulphates and chlorides will not adhere to the soil. As we can see in later sections, both nitrate and chloride contents are low to moderate across the site.

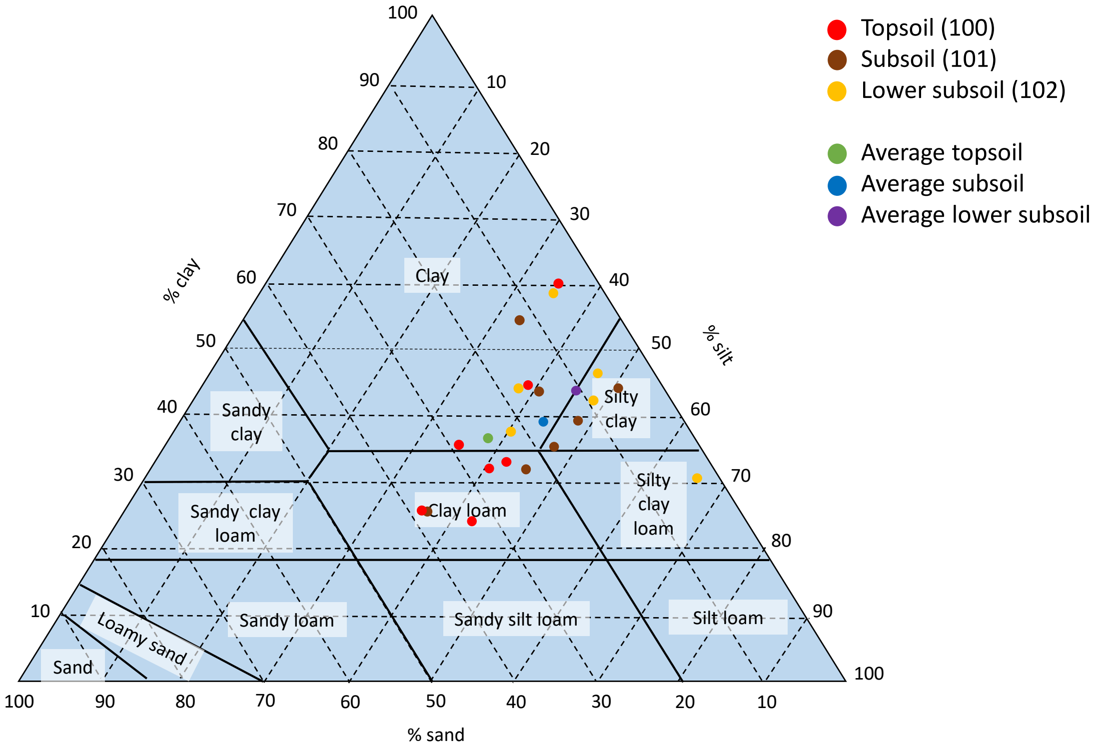


Figure 189: Texture triangle for selected samples from the site analysed using a Malvern Mastersizer. Topsoils are predominantly clays and clay loams.

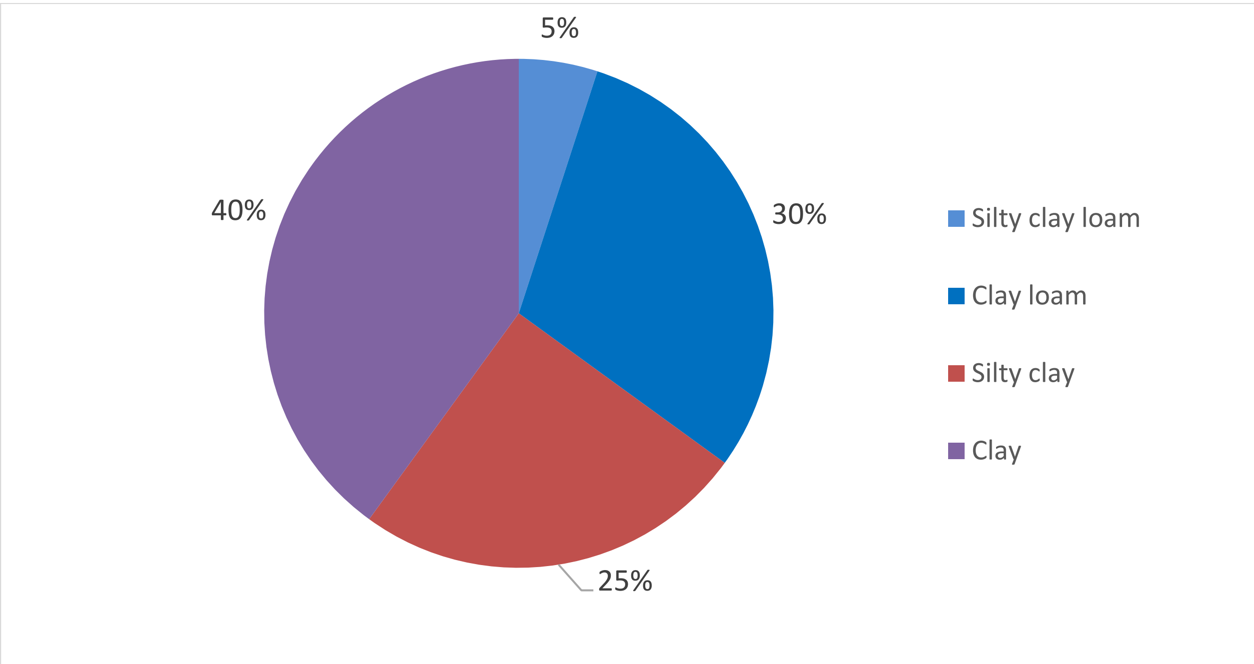


Figure 190: Texture classes of Edgehill soils from Malvern Mastersizer. All soils were identified as a type of clay.

6.7.5.1 Texture against bullet condition

If the clay content of the soil is plotted against the condition of lead bullets, a slight positive correlation is present, though it is only slight (figure 191). The coefficient for the relationship is 0.224 which indicates a slight positive correlation with condition score increasing with clay content, but this value is not statistically significant (table 64).

The sand content of soil was also compared to the condition score of bullets from the site, which showed a very slight negative correlation with condition score reducing as sand content increased (figure 192). This is not what would be expected as sand content tends to increase the corrosion of metals. However, this relationship is weak and the coefficient is -0.159 (table 65) which is not statistically significant.

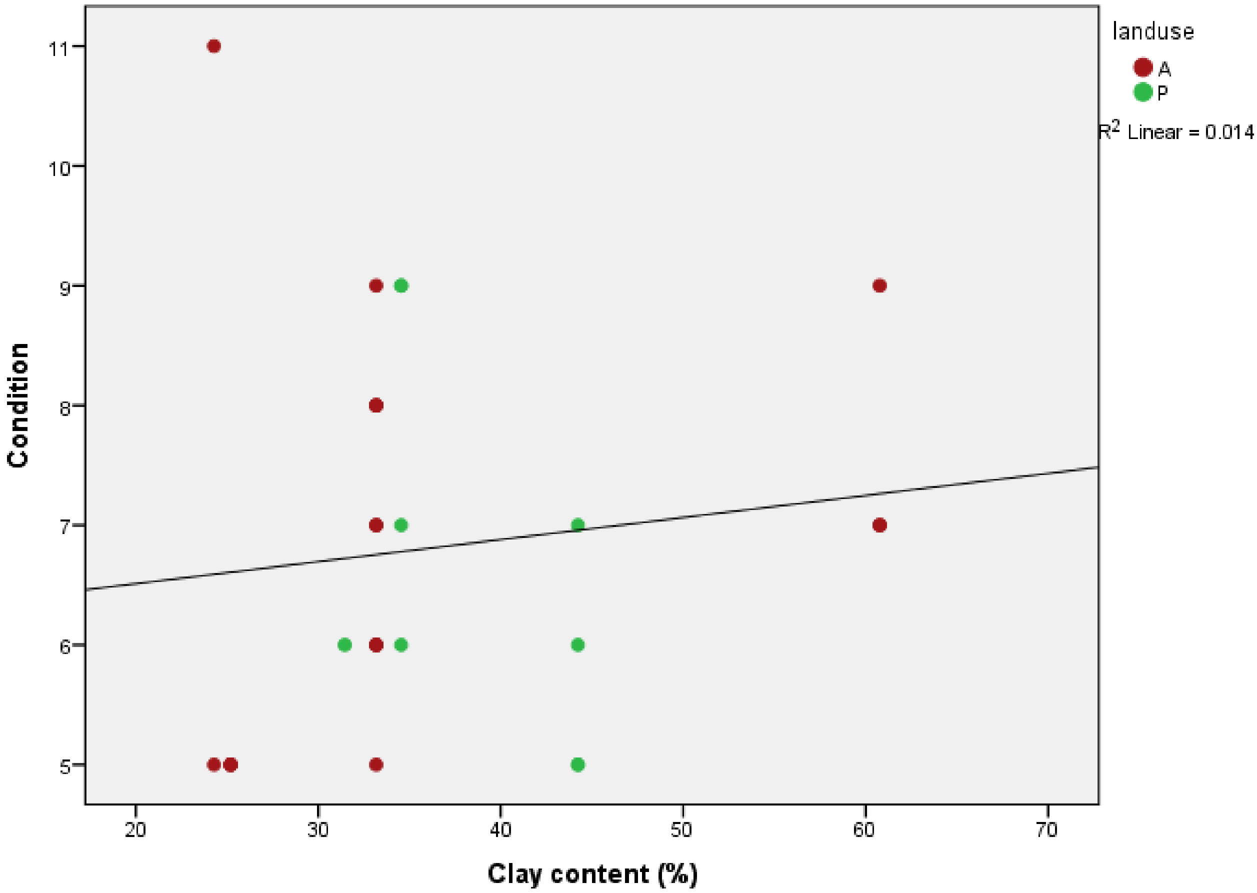


Figure 191: Scatter plot showing the clay content of soil against the condition of bullets, showing a very slight positive correlation, with condition worsening with increasing clay content.

			Condition	Clay
Spearman's rho	Condition	Correlation Coefficient	1.000	.224
		Sig. (2-tailed)	.	.262
		N	95	27
	Clay	Correlation Coefficient	.224	1.000
		Sig. (2-tailed)	.262	.
		N	27	27

Table 64: Spearman's rank correlation coefficient of 0.224 between clay content of soil and bullet condition, which is not statistically significant.

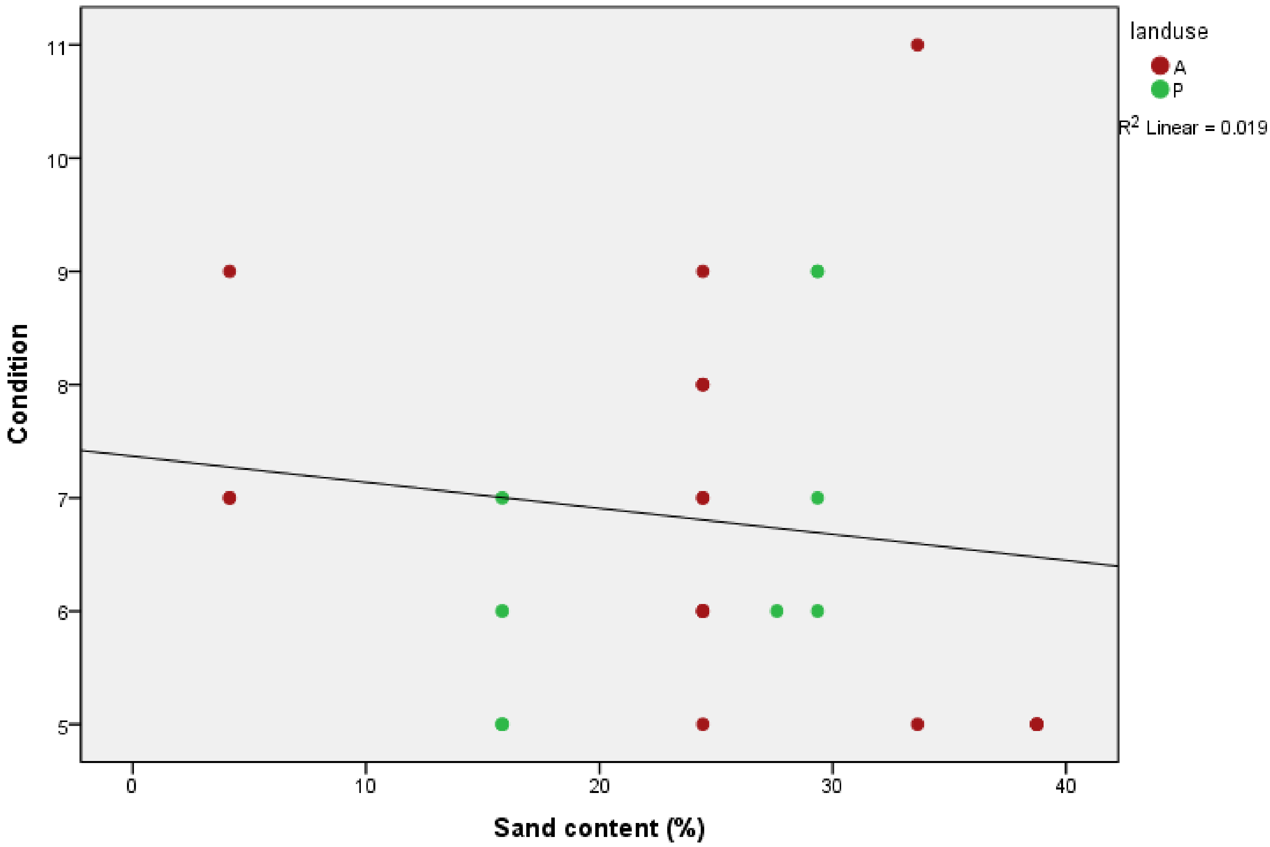


Figure 192: Scatter plot showing the sand content of soil against the condition of bullets, showing a slight negative correlation, with condition improving with increasing sand content.

			Condition	Sand
Spearman's rho	Condition	Correlation Coefficient	1.000	-.159
		Sig. (2-tailed)	.	.429
		N	95	27
	Sand	Correlation Coefficient	-.159	1.000
		Sig. (2-tailed)	.429	.
		N	27	27

Table 65: Spearman's rank correlation coefficient of -0.159 between the sand content of soil and bullet condition, which is not statistically significant.

6.7.6 Nitrate content results

Nitrate levels range in soils from 11.60mg/kg to 474.17mg/kg. Topsoil levels average at 198.17±145.63mg/kg, subsoils average at 48.62±13.18mg/kg and lower subsoils average at 23.00±7.84mg/kg. Levels are distinctively higher in the topsoil than lower deposits where the levels fall drastically (figure 193). This fall in nitrate levels with soil depth is also seen at Moreton Corbet and indicates a leaching of nitrates or uptake of nitrates from roots from lower soil profiles (Addiscott, Whitmore, and Powlson 1991). Nitrate levels are significantly higher in topsoil deposits, which could have a damaging effect on the condition of lead bullets. Nitrate levels of 160mg/kg and above is deemed a relatively high level of nitrates for soils (Agricultural and Horticultural Development Board 2017). 57% of topsoil measurements were recorded as above this level, which may have an effect on the preservation of lead.

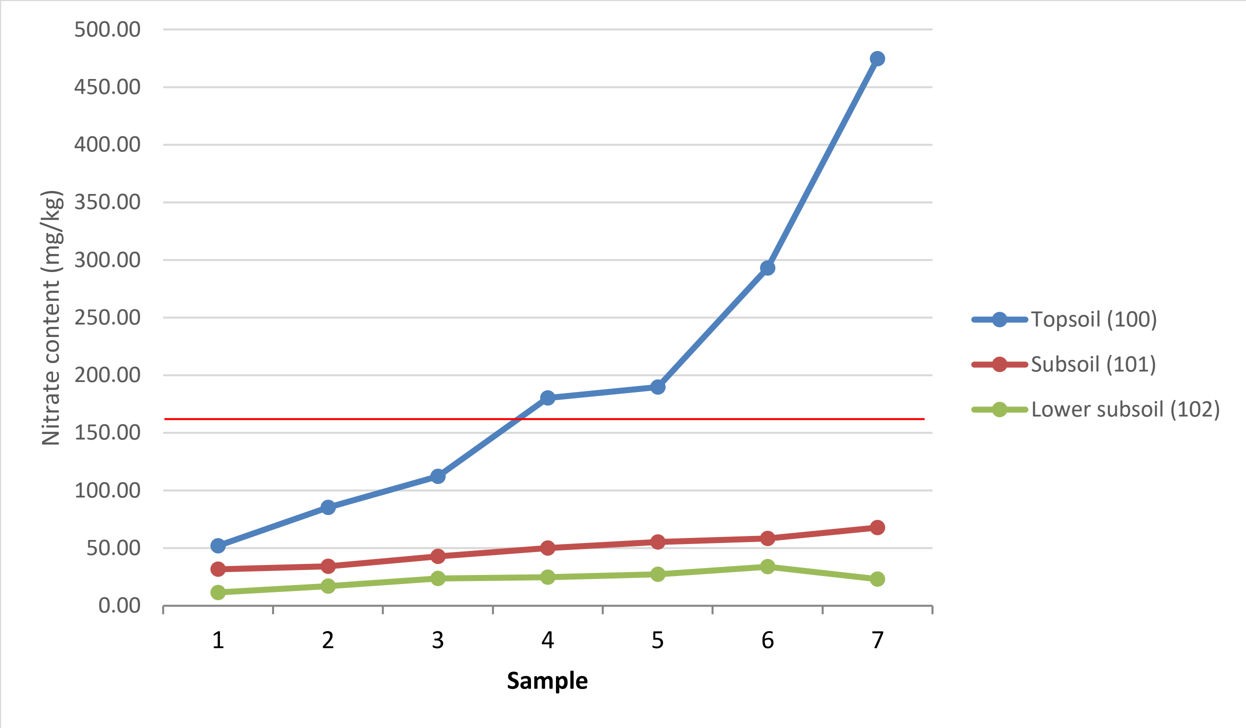


Figure 193: Nitrate concentration of soil layers across the site, indicating a large drop in concentration in subsoil and lower subsoils. The red line indicates a relatively high level of nitrates for soils (Agricultural and Horticultural Development Board 2017).

6.7.6.1 Nitrate content against bullet condition

Nitrate levels in the soil at Edgehill range from very low to relatively high in topsoils. As there were low levels of conductivity in pasture fields, there is a similar consistently low level of nitrate in pasture fields across the site (figure 194). On average, nitrate content in arable fields across the site measures 284.37±136.72mg/kg, whilst levels only average 83.23±30.13mg/kg on long term pasture fields. This is likely to be down to the lack of application of nitrate fertiliser to the pasture fields.

If the relationship between the conditions of bullets is compared to the nitrate contents of the soil, there is no clear trend, apart from the already mentioned difference in land use (figure 195). The coefficient for this relationship is 0.088 which is near to 0 and indicates no statistically significant correlation (table 66). However, the low level of nitrates in pasture fields is likely to be a factor in the improved condition of lead bullets in these fields and could have an impact on their long term preservation.

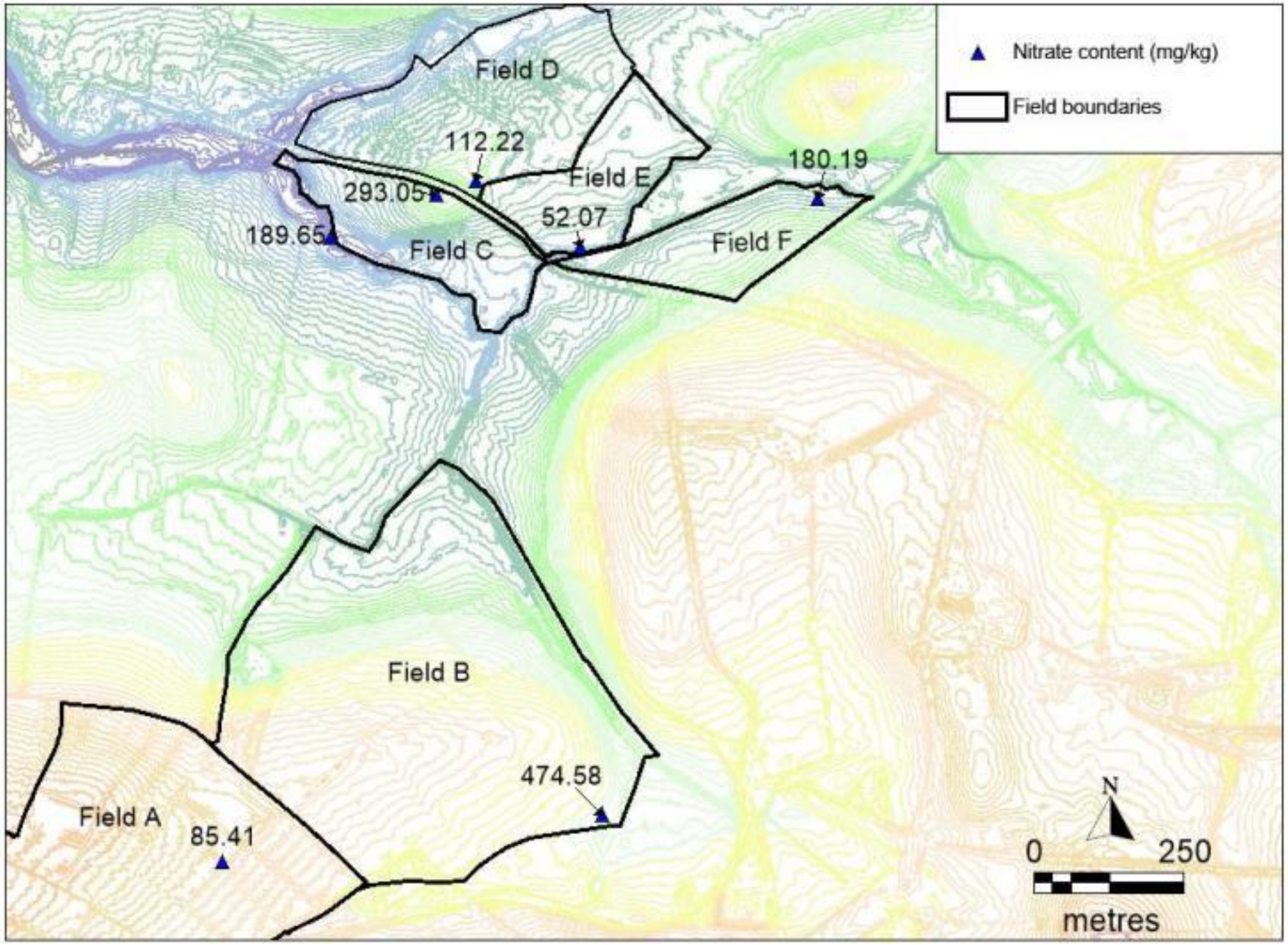


Figure 194: Nitrate concentration (mg/kg) of topsoil samples across the site. Levels are consistently higher in arable fields. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

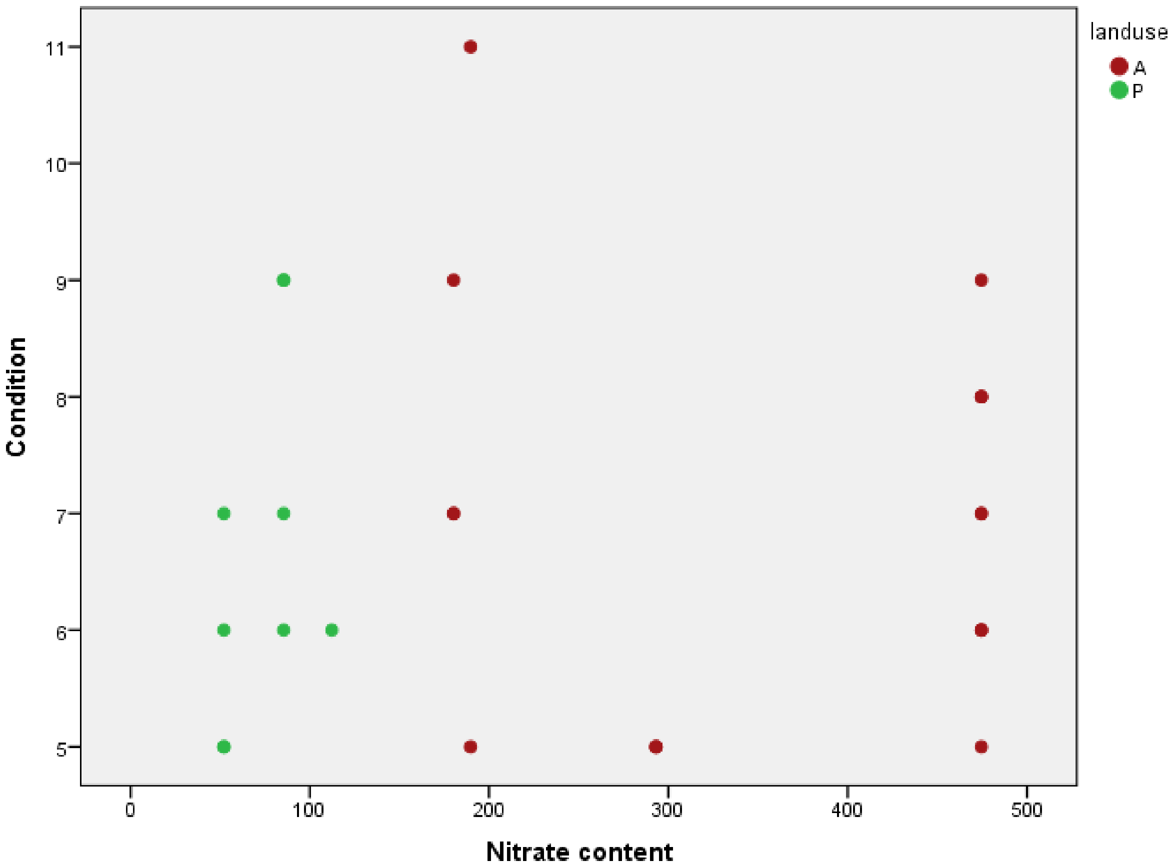


Figure 195: Scatter plot showing the nitrate content of soil against the condition of bullets, showing no clear trend. It does indicate that the lowest levels of nitrates are consistently on pasture fields. (A=arable, P=pasture).

			Condition	Nitrate
Spearman's rho	Condition	Correlation Coefficient	1.000	.088
		Sig. (2-tailed)	.	.662
		N	95	27
	Nitrate	Correlation Coefficient	.088	1.000
		Sig. (2-tailed)	.662	.
		N	27	27

Table 66: Spearman's rank correlation coefficient of 0.088 for condition of bullets against nitrate content in soil, with no statistical significance.

6.7.7 Chloride content results

Chloride content in soils range from 53.86mg/kg to 84.54mg/kg; a low to moderate level. Topsoils average at 73.87±6.52mg/kg, subsoils average at 69.74±8.84mg/kg, and lower subsoils average at 62.45±8.02mg/kg, indicating that levels did not drop significantly with soil depth (figure 196), unlike nitrate levels which dropped severely in lower contexts. This suggests that soil is better at retaining chlorides than they are at retaining nitrates which easily leach out of the soil column. All chloride levels at the site are not high as readings above 100mg/kg are deemed as a moderate level in soils (Schulte 1999) (figure 197).

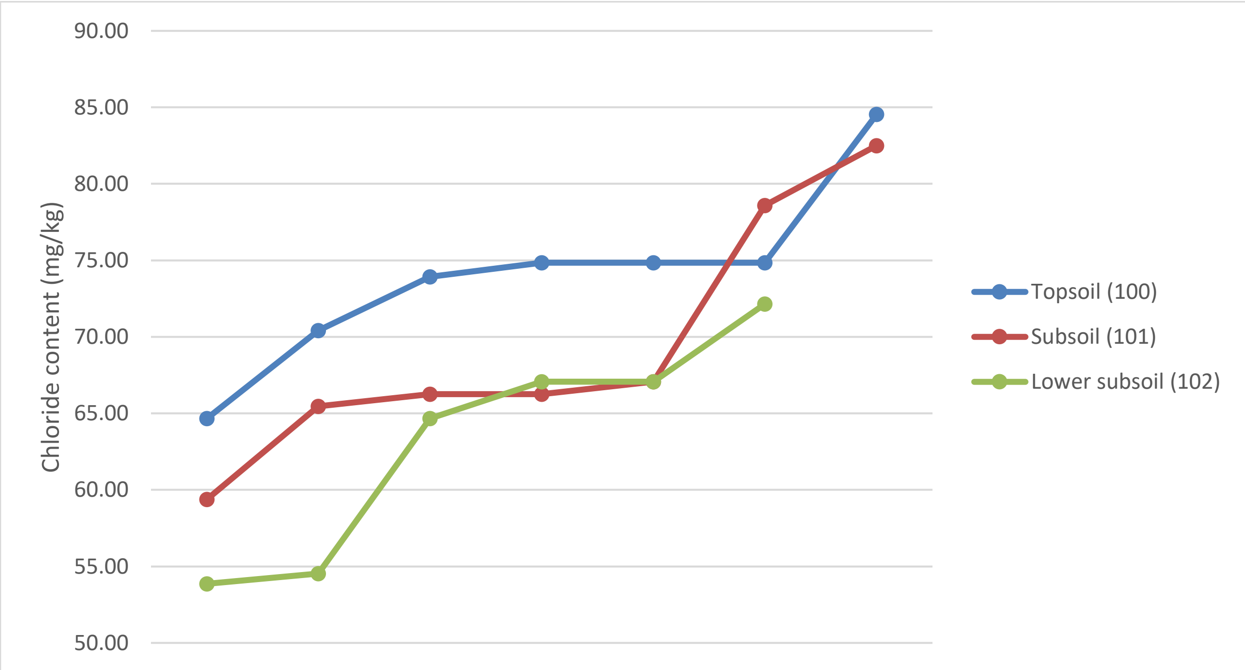


Figure 196: Chloride content of soils sampled, indicating variations throughout the soil profile. Levels over 100mg/kg are deemed moderate levels of chlorides and all recorded at Edgehill are relatively low.

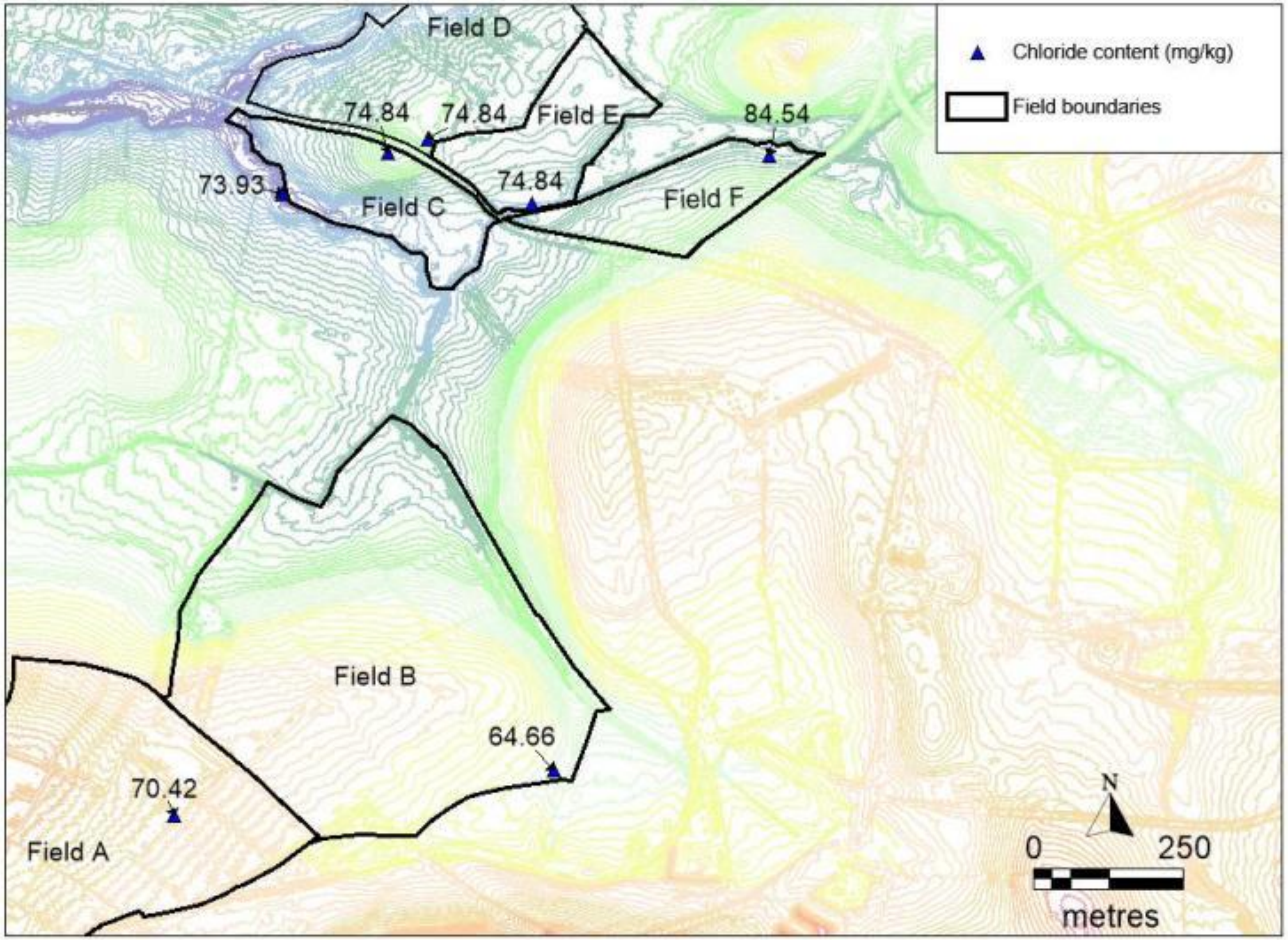


Figure 197: Chloride concentration (mg/kg) of topsoil samples across the site, indicating that relatively low levels were recorded across all fields. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

6.7.7.1 Chloride content against bullet condition

The chloride content of the Edgehill soils are relatively low, though it remains unclear at what concentration chlorides need to be at to be have an impact on lead preservation (Pollard *et al*. 2006). When the chloride content is plotted against the condition of the lead bullets, there is a very slight negative correlation, with condition improving with increased chloride levels (figure 198). This is not what was expected as the mobile chloride ions can initiate serious corrosion issues. In this case however, they do not appear to be significant. The coefficient value for this relationship is -0.215 (table 67) which is not statistically significant.

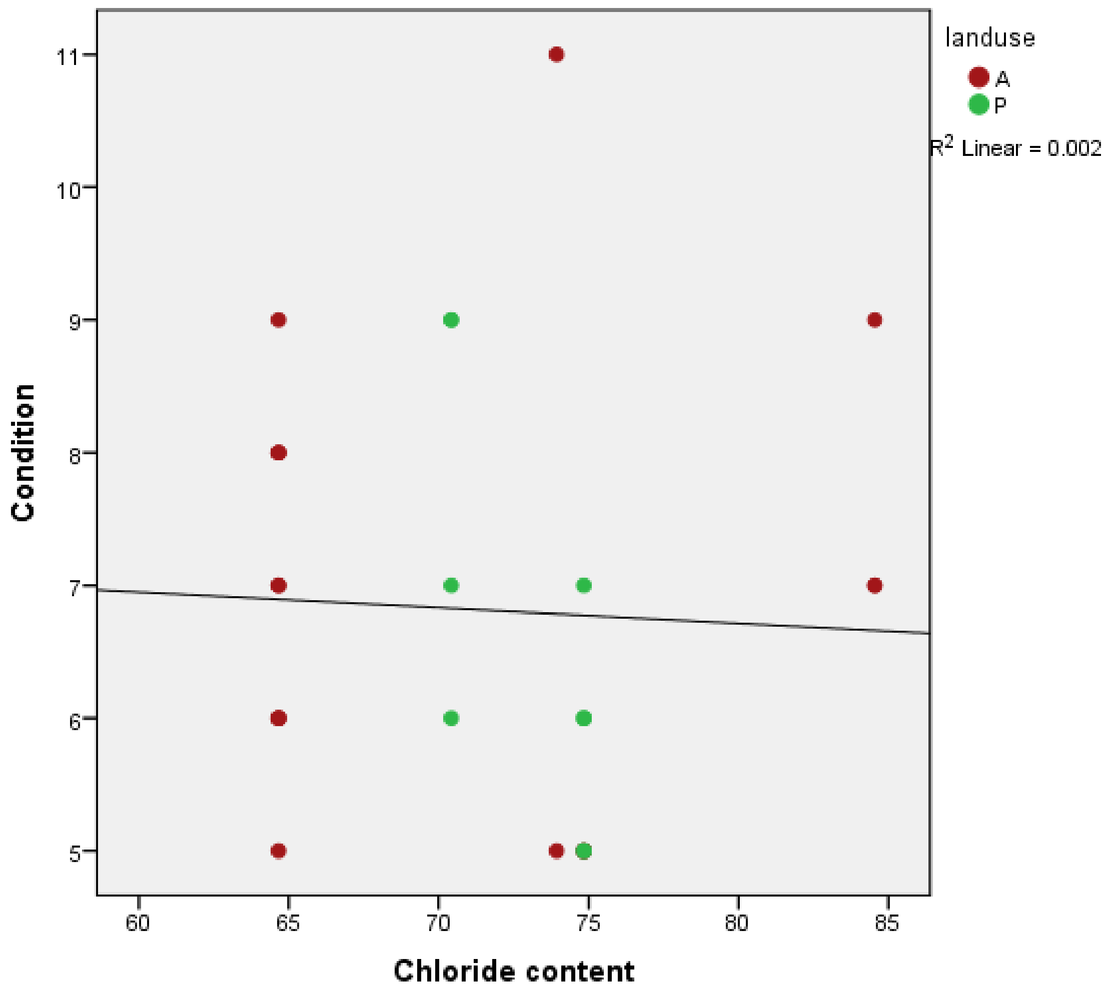


Figure 198: Scatter plot showing the chloride content of soil against the condition of bullets, showing a slight negative correlation, but no strong trend.

			Condition	Chloride
Spearman's rho	Condition	Correlation Coefficient	1.000	-.215
		Sig. (2-tailed)	.	.282
		N	95	27
	Chloride	Correlation Coefficient	-.215	1.000
		Sig. (2-tailed)	.282	.
		N	27	27

Table 67: Spearman's rank correlation coefficient of -0.215 between the soil chloride content and the condition of bullets, which is not statistically significant.

6.7.8 Statistical overview

Comparing the soil parameters with the condition of bullets from Edgehill, very few significant relationships are apparent. This is mainly due to the sheer quality of preservation on the site; the range in condition is not great enough to reveal any trends and it is not possible to identify key soil parameters in terms of preservation.

Aspects that do stand out at this site however, include the texture, pH and land use. Apart from Field F which exhibits acidic soils, the site is slightly alkaline, which promotes the preservation of lead. The soil across the entire site is a type of clay, which should promote the preservation of lead by restricting oxygen and water flow through the soil column (Kibblewhite, Toth, and Hermann 2015). Furthermore, through the above analysis, several patterns have been identified based on the historic land use of the site. Long term pasture fields have consistently lower conductivity levels and lower level of nitrates in the topsoil. Condition is also better in areas of long term pasture. Further spatial analysis of each field may identify patterns which did not emerge during statistical analysis.

6.8 Spatial analysis

As discussed above, no significant patterns could be identified through statistical analysis of soil parameters at Edgehill. In order to assess any patterns which occur field by field on the battlefield, spatial analysis was also conducted, assessing the land use history of each field alongside their soil conditions and the condition of bullets.

6.8.1 Pasture fields

6.8.1.1 Field A

Field A has not been cultivated since at least 1733 and contains extremely well preserved medieval ridge and furrow. 24 bullets were analysed from this field. All scored a condition of very good (1) or good (2) with an average score of 1.16±0.03 across the field. 20 bullets scored a 1 of very good condition, whilst 4 scored a 2 for good condition, indicating the excellent level of preservation in this field. Only one bullet from the field had any evidence of being abraded (figure 199).

The topsoil conditions vary across Field A. pH ranges from 6.28 to 7.69, indicating that over a distance of 500m conditions vary from neutral to alkaline. These pH levels are not detrimental in terms of metal corrosion as they do not fall below the pH 5.5 and therefore are optimum pH levels for the preservation of lead. Conductivity ranges from 24.73µS/cm to 68.63µS/cm which is low compared to other areas of the site. Conductivity is fairly consistent across the eastern side of the field, but drops to the west which is likely to be due to a decline in water content. No conductivity level in the field is particularly high and would not promote acceleration of corrosion. Water content ranges from 17.94% to 25.39% and is lower to the western side of the field. Water levels to the east are moderate in terms of soil aggressiveness. Organic content in this field is very consistent, ranging from 12.12% to 12.95% and is the highest levels of any part of the site investigated. One test pit was sampled for chloride and nitrate content, recorded at 70.42mg/kg and 85.41mg/kg respectively, which are relatively low levels of ions.

None of the soil results from Field A relate to an aggressive soil environment. The majority of the field is alkaline with relatively low levels of conductivity and relatively low anion content. Water content is reasonable across the field, retained by the silty clay texture of the soil, but this is not likely to create a damaging environment for metal without a corresponding high level of conductivity. As this field has excellent remnants of ridge and furrow which has not been ploughed since at least 1733, with the relatively benign soil conditions it is not surprising that the bullets in this field are very well preserved.

Due to the soil being silty clays and clay loams, and the lack of cultivation in this field, oxygen will be depleted in the soil profile. Furthermore, bullets in pasture which has not been cultivated will graduate to the bottom of the topsoil meaning they are less exposed to oxygen levels further up the soil column. Clay soils contain small plate-like particles which are prone to compaction and often have restricted drainage and oxygen flow. Soils in this field were recorded as olives and dark greys, indicating a reduced level of oxygen. This could be very significant in terms of the preservation of lead bullets as a lack of oxygen will mean corrosion is less likely to take place. It appears that preservation is excellent in this field due to its maintained use in long term pasture, allowing bullets to sit further down the soil column in oxygen-depleted surroundings. The lack of ploughing has kept oxygen levels down, and the lack of fertilisation has allowed nitrate and conductivity levels to remain low. Preservation is also aided by the alkaline clay nature of the soil.

6.8.1.2 Field D

The ridge and furrow in Field D is very well preserved and all evidence suggests that it has not been ploughed since well before 1789. One section to the south of the field has been pasture since at least the 1940s, but does not contain any surviving ridge and furrow and therefore must have been ploughed at some point between 1789 and 1947. This field is incorporated into the main field by 1993 and all are in use as pasture. However, no bullets have been retrieved from this area of pasture and therefore no comparison can be made between this area and the area to the north with surviving ridge and furrow.

Only three bullets were recovered from this field, all of which scored either a 1 for very good or 2 for good condition, none of which were recorded as being abraded (figure 200). The small number of bullets recorded is likely to be due to most material residing at the bottom of the topsoil as a lack of cultivation has allowed bullets to settle further down the soil profile, thus often out of metal detector range. Only two test pits were dug in this field due to the lack of data available. One pit was excavated in permanent ridge and furrow and one in the pasture area with no surviving ridge and furrow to assess the difference in soil conditions between permanent ridge and furrow and permanent pasture.

pH varied considerably between the test pits, from pH 5.72 in the ridge and furrow, to pH 7.38 in the short term pasture area. 5.72 is considerable lower than the majority of pH readings from the battlefield, but still would not theoretically promote the acceleration of corrosion of metal. Conductivity is fairly low ranging from 50.53 μS/cm and 85.43uS/cm across the field. Water content is similar in both areas of the field, between 20.88% and 21.83%. Organic content ranges from 9.72% to 11.22%. Chloride and nitrate content are at moderate levels, measuring 74.84mg/kg and 112.22mg/kg respectively.

Most of the soil measurements in Field D would not cause an issue with the preservation of buried lead. However, the pH in the ridge and furrow area of the field is surprisingly low compared to the rest of the site and is low enough to potentially trigger deterioration of lead, but not accelerate it. Besides a difference in pH levels, conditions varied little between the area of long term permanent pasture and the area of short term pasture which has been cultivated sometime between 1789 and 1947. This suggests that converting to pasture even in the short term could help preserve the condition of buried bullets. Unfortunately only three bullets were recovered from this field and so conclusions are limited. Further detecting and sampling in this field was not practicable within this study, but could provide further data to develop stronger conclusions.

6.8.1.3 Field E

In the 1940s Field E comprised two separate fields partitioned by a hedgerow. The field to the north had very distinct ridge and furrow, whilst the field to the south had no ridge and furrow visible which indicates the field has been ploughed sometime between 1789 and 1947. This boundary had been removed by 1985 and all trace of ridge and furrow has been lost by 1993. This field has however been returned to pasture.

Four bullets were recovered from the southern end of this field, all of which scored a 1 for very good condition with no significant corrosion or abraded surfaces (figure 200). This field has clearly been ploughed at some point in the 19th century due to the loss of medieval ridge and furrow evidence. Nonetheless, the bullets retrieved from this field are in excellent condition, similar to bullets in Field A. Therefore, the key to their survival is likely to be the continued use as pasture throughout the 20th and 21st centuries.

pH in Field E ranges from 6.10 to 7.31. Conductivity was fairly consistent, recorded between 56.50uS/cm and 61.63 μS/cm. Water content ranges from 22.34% to 28.48% which is relatively high. Organic content ranges from 9.65% to 11.76%. Chloride and nitrate content was recorded at 74.84mg/kg and 52.07mg/kg respectively, which are low to moderate levels.

In terms of soil aggressiveness, this field does not pose a threat to the preservation of metals. Only four bullets were recovered from this field and all were recorded as in very good condition. This field has been under pasture since at least the 1940s and appears to be the overarching factor enabling the preservation of bullets in this field.

6.8.2 Arable Fields

6.8.2.1 Field B

In the 1940s this field comprised five distinct fields, all of which contained distinct ridge and furrow. By 1961 part of the eastern edge of the field had been converted to arable, but the majority still contained ridge and furrow. By 1985 the fields had been amalgamated into two arable fields and are still in used as arable to the present day.

38 bullets were analysed from this field. All scored a condition of very good (1) or good (2) with an average score of 1.44±0.05 across the field (figure 199). Four bullets showed signs of abrasion to their surfaces suggesting that movement and attrition in this field is more common than in pasture fields, but is still only slight.

Soil conditions vary across Field B. pH ranges from 6.49 to 7.60 which is a benign range of pH in terms of metal corrosion. Conductivity ranges greatly from 89.20µS/cm to 427.67uS/cm, which increases to the eastern end of the field. This area denotes a change on topography as the field slopes downhill to the east from a height of 89m to 82m AOD towards the edge of the field where a river channel curves round the field boundary. The high conductivity levels in this region of the field could certainly promote the corrosion of lead. Water content ranges from 16.24% to 27.42% across the field, again the highest levels of which are found in down slope areas to the east. The higher water levels and conductivity in the eastern side of Field B may promote the corrosion of lead bullets, greater than other areas of the battlefield.

The majority of the soil results do not indicate a particularly aggressive environment for buried metals. However, test pits Ba2 and Ba3 to the eastern slope edge of Field B contain relatively high conductivity and water contents. Chloride and nitrate contents were also taken for test pit Ba3 which were 64.66mg/kg and 474.58mg/kg respectively. This level of nitrate concentration in the topsoil is high and this field contains the highest levels of nitrates across the whole site. These levels of water conductivity and nitrates would suggest that metal condition may be worse in this area of the field. This area of the field is one of the lowest parts of the site in terms of topography and may also be vulnerable to water table fluctuations.

Across the field, 20 bullets are recorded as in very good condition (1), and 18 are recorded as good condition (2). Though all bullets are relatively well preserved, this equates to a 27% increase in bullets scoring a 2 instead of a 1 for condition compared to those in Field A which is under permanent pasture. Average bullet condition in Field B is worse than Field A, with average condition results of 1.44 and 1.16 respectively.

Field B may represent a very gradual decline in object condition since its conversion to arable in the 1970s. It was shown at Moreton Corbet that a shift to arable cultivation appears to have accelerated the deterioration of lead bullets at the site. It appears that the conversion to arable has resulted in a slight decline in bullet condition, but the soil conditions at Edgehill of alkaline clays have buffered against any severe deterioration by reducing the effect of abrasion from soil particles.

6.8.2.2 Field C

This field has not changed in terms of boundaries since at least the 1940s when distinct ridge and furrow was still present. This field had been ploughed by 1976 (National Monuments Record aerial photograph SP 3451/1 35 1976). It remains in arable use to the present day.

Nine bullets were analysed from this field. Seven scored a 1 for very good condition, with one scoring good (2) and one scoring fair (3). One bullet was identified as having an abraded surface and one had evidence of localised corrosion.

The soil conditions across Field C remain fairly consistent. pH ranges from 7.30 to 7.54 indicating that the field is consistently alkaline and would not pose a threat to the preservation of lead bullets. Conductivity ranges from 113.07μS/cm to 182.73μS/cm which is not benign but not particularly high. Water content varies from 20.03% to 25.97%. Organic content is fairly low, between 8.39% and 9.02%. Chloride and nitrate content was measured in test pit Ca1 and recorded as 74.54mg/kg and 298.05mg/kg respectively.

In terms of soil aggressiveness, this field appears fairly benign. It is consistently alkaline with moderate conductivity and water levels. Nitrate content appears fairly high at 298.05mg/kg. Seven of the nine bullets from this field scored a 1 for very good condition, indicating a good level of preservation. This may be surprising as the field has been under cultivation for at least the last four decades and appears to be in a similar condition to bullets in pasture fields. It is however, interesting that this field contains the only bullet to score lower than a 2 for overall condition. No environmental factors point to this field being an aggressive soil environment. However, both bullets which score less than a 1 for condition are located down slope and close to the stream course running along the southern extent of the field boundary (figure 200). The field slopes quite dramatically from the top of the field at 83m AOD to 75m AOD at the base of the slope to the southern end of the field. It may be that bullets have been displaced down slope through cultivation episodes. The vicinity to the stream may also suggest that bullets down slope may be vulnerable to fluctuations in the water table during the year, which would encourage corrosion.

6.8.2.3 Field F

The 1940s RAF aerial photographs show that this field only contains slight traces of ridge and furrow which indicates that this field has been ploughed sometime between 1789 and 1947 (RAF aerial vertical CPE/UK 1926 2094 1947). It appears to have mainly been in use as pasture through the 20th century, but was converted back to arable cultivation by at least 1993 and remains arable to the present day.

14 bullets were retrieved from this field, with the average condition score being 1.46±0.03, which is the highest of all the fields. Four bullets also showed signs of abraded surfaces, indicating that though condition is not poor in this field, it is in general the worst of the fields investigated in this study (figure 200).

pH ranges dramatically in this field, from 4.86 to 6.10. This is significantly more acidic than the majority of the site which averages in the topsoil at 6.91. pH 4.86 is particularly acidic and would promote the breakdown of lead in the soil and promote corrosion acceleration. It is unclear whether this one sample is an anomaly or whether the pH is significantly more acidic in this area. Only further sampling in future would verify this.

Conductivity ranges from 96.67uS/cm to 131.60uS/cm which is moderate. Water content ranges from 20.16% to 21.66% and organic content ranges from 10.65% to 11.05%. Chloride and nitrate content were measured in test pit F2 at 84.54mg/kg and 180.19mg/kg respectively which are at moderate levels.

It appears that though condition is not poor in this field, it is the worst of the fields investigated in this study. Bullets averaged in condition at 1.46 which is higher than any other field. It also contains the most abraded bullets, totalling four. The likely explanation for this is the cultivation of the field since 1789. As no ridge and furrow exists in the 1940s, it appears that this field may have been cultivated more frequently than all the other fields investigated. However, it has been under a similar if not shorter period under the plough in the 20th century. Periods of non-cultivation will have allowed the bullets to once again migrate vertically down the soil column to more benign soil environments, but once ploughed again, the bullets will have yet again been disturbed and been brought to the soil surface. It seems likely that cultivation is the main reason why condition is generally worse in this field, though the acidity may also have accelerated this process and allowed bullets to deteriorate slightly faster than those in Field B. It may be that as this field continues to be ploughed over the next few decades, the bullets will continue to deteriorate due to the acidic levels and the regular cultivation.

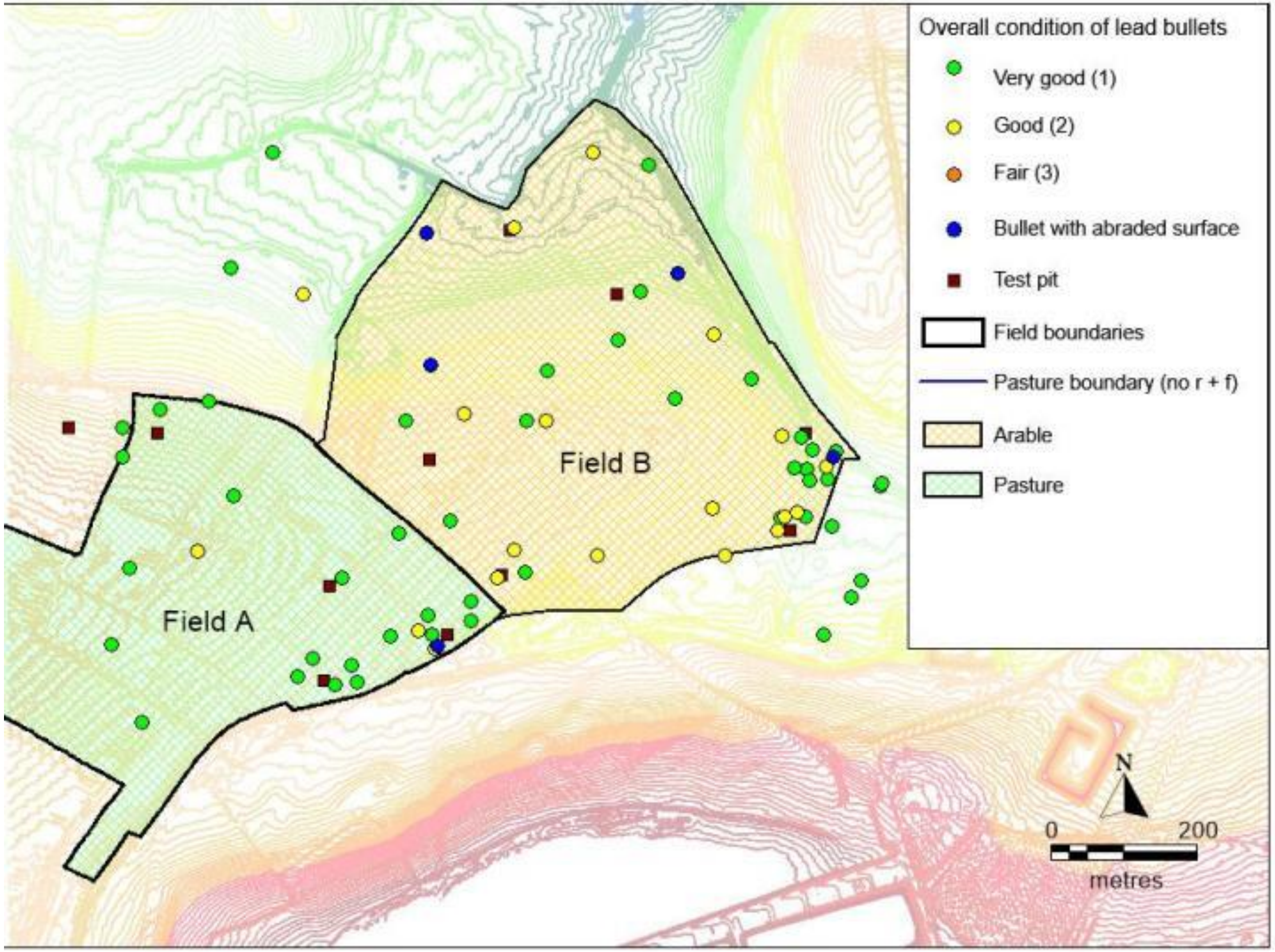


Figure 199: Distribution of lead bullets and corresponding condition scores across fields A and B. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

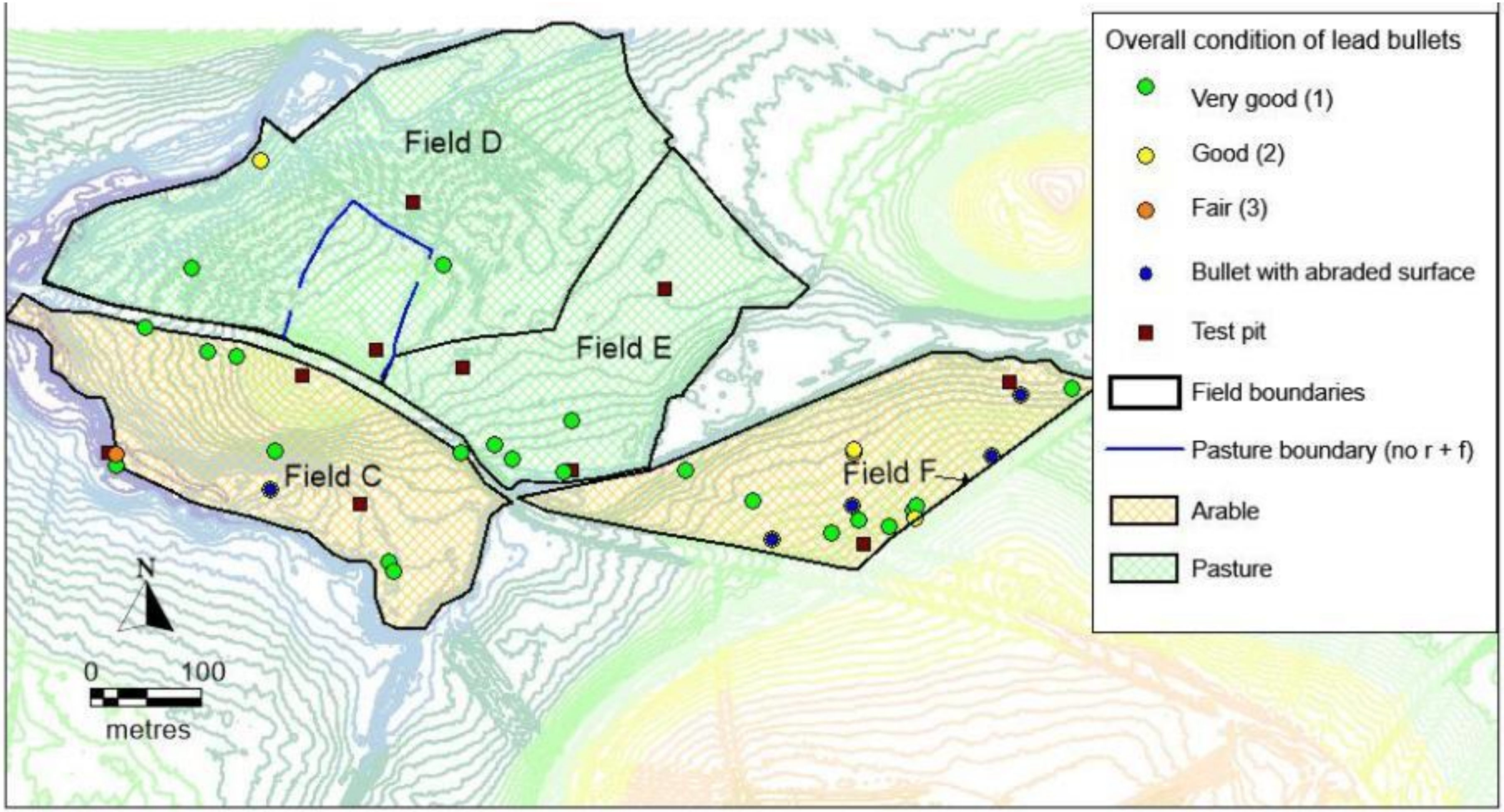


Figure 200: Distribution of lead bullets and corresponding condition scores across fields C, D, E and F. Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

6.9 Overview of the battlefield of Edgehill

Though statistical analysis revealed no significant correlations between the burial environment and the condition of bullets at Edgehill, this is due to the fact that 99% of the bullets scored a 1 or 2 for condition and the preservation did not vary enough to highlight any significant trends. Statistical analysis may result in more fruitful results with a larger sample size in future, and in chapter 8 the data is shown to be statistically significant when adding in results from Moreton Corbet and Wareham which exhibit very different soil environments. Nevertheless, spatial analysis of the data indicates reasons for the excellent preservation at this site.

The most noticeable difference in burial environments across the battlefield is land use. Bullets located in permanent pasture are in better condition than those under arable. The key to their preservation is also down to the nature of the soil. Alkaline clays with impeded drainage and oxygen flow will reduce the rate of corrosion in the soil, especially if the bullets have resided near the bottom of the topsoil layer for hundreds of years, restricting their access to oxygen. Nonetheless, even on arable fields bullet condition is still very good. One reason for this may be the nature of clays; when cultivated, sandy soils break apart, allowing oxygen and water to flow easily through the soil column. However, clays tend to move as peds in the ground which will continue to reduce oxygen flow as the soil is moved as clumps in the field. This also makes objects less prone to abrasion from sandy particles (Dunnell 1990, 593). Poor aeration in clay soils is also likely to result in a slow corrosion rate over long periods of burial due to oxygen deficiency (Gerwin and Baumhauer 2000, 76). However, condition is still in general better in long term pasture. There is an 84% chance of a bullet being in very good condition (1) in pasture, whilst in arable this chance drops to 59%.

The key to the survival of bullets at Edgehill is the preservation of their protective patinas. The patina has stayed intact due to clay rich soils and the lack of abrasion induced on the bullet surfaces. Average clay content of soil at Edgehill is 39.24±10.47%, whereas as Moreton Corbet this average drops to 23.34±4.38%. This average content drops significantly at Wareham to an average clay content of 6.99±1.22% with a corresponding increase in the number of abraded bullets (see chapter 7). It appears that as clay content declines, abrasion of bullets increases accordingly.

This highlights the importance of maintaining current burial conditions. Bullets at Edgehill have suffered little abrasion damage, which only increases in arable areas. If arable cultivation is having an impact on the condition of bullets at Edgehill, the effects are very slow and it may take several decades of cultivation to cause any lasting damage. However, over the long term, maintained cultivation will allow bullets to deteriorate and issues such as abrasion to bullet surfaces will only increase with prolonged cultivation activities. Evidence from Edgehill has shown that condition is improved in long term pasture. Therefore, pasture should be retained in its current use and cultivated areas should be converted to pasture to secure the long term survival of the battlefield material. This change in land use is perhaps a more pressing issue in sand-dominated environments where abrasion is a serious issue for the long term survival of bullets.

7 Wareham siege site

7.1 Introduction

The site of Bestwall quarry is located 0.5km east of Wareham in south-east Dorset. Between 1992 and 2005 archaeological rescue work was carried out at the 55 hectare site during the construction of a gravel quarry. During the Civil War the town of Wareham was fortified as a garrison. The settlement was initially held by the Parliamentarians and captured by the Royalists which led to the Parliamentarians making attempts at regaining the town. The evidence of conflict at the site of Bestwall quarry is likely to be the result of two sieges which took place in the summer of 1644 involving a few hundred troops when Parliamentarians attempted to make the Royalists surrender (Ladle 2012, 330).

A total of 559 lead bullets have been retrieved from the site, the majority of which are likely to be from Civil War conflict (Ladle 2012, 144). Finds were collected through metal detecting using a 25mx25m grid system and recorded by field, without exact locations being recorded due to the rescue nature of excavation (Ladle Pers. Comm. 10.10.2016). As a result of quarry construction destroying the site and lack of exact object location data, fieldwork for this project was limited and soil samples had to be collected as close to the site as possible without sampling contaminated areas. Therefore analysis of soil conditions is restricted and condition of material could not be mapped across the landscape. Nonetheless the Wareham lead bullets provide interesting information on the preservation of lead bullets in a contrasting environment to Edgehill and Moreton Corbet. The bullets have already been noted as being in very poor condition (Foard 2012, 119; Foard and Morris 2012, 141).

Since 2012 the bullet collection has been under the care of Dorset County Museum and stored in individual bags in airtight boxes containing silica gel. The storage of the bullets is unclear between 2005 and 2012, but it is likely the bullets were stored as bulk finds in large bags which have allowed the bullets to suffer post excavation decay (Ladle pers. Comm.. 10.10.2016). This needs to be taken into consideration when reviewing the reasons behind their current condition.

Wareham was chosen as a site for assessment due to the noticeable poor condition of the lead bullets. The landscape itself provides an excellent contrast to the battlefield of Edgehill as the siege site of Wareham resides in very low-lying ground in an area of acidic sands and has seen decades of almost constant cultivation.

7.2 Landscape

The siege site of Wareham lies on a low ridge of valley gravels on a floodplain between the two rivers Frome and Piddle, and is overlain by superficial alluvial free draining sand and gravel deposits (British Geological Survey 2017; Ladle and Woodward 2009, 1; Cranfield University 2016; Ordnance Survey of England and Wales 1910). The area has a mild and temperate climate with average annual rainfall of 829.4mm (Met Office 2017). The area under investigation is flat and low lying, only reaching heights of 0-6.0m AOD. This means that the site is prone to flooding; most of the quarry now forms a filled in lake. The place name of 'Wareham' originates from a 'village' on a 'weir', which associates the settlement with the rivers and floodplain (Ekwall 1960, 497).

7.3 Field Methodology

Fieldwork was carried out in October 2016 at Wareham to collect soil samples. Due to the severe destruction and contamination of the site through quarry construction no soil samples from the locations of lead bullets could be collected due to lack of access to the site and the fact that the soil has been removed, manipulated and contaminated. Therefore, background samples of the general soil conditions were collected on the very edge of the quarry extent (figure 201). Three test pits were dug, with four soil horizons identified in each pit. The soil was extremely loose and dry upon excavation and extraction with an auger proved difficult.

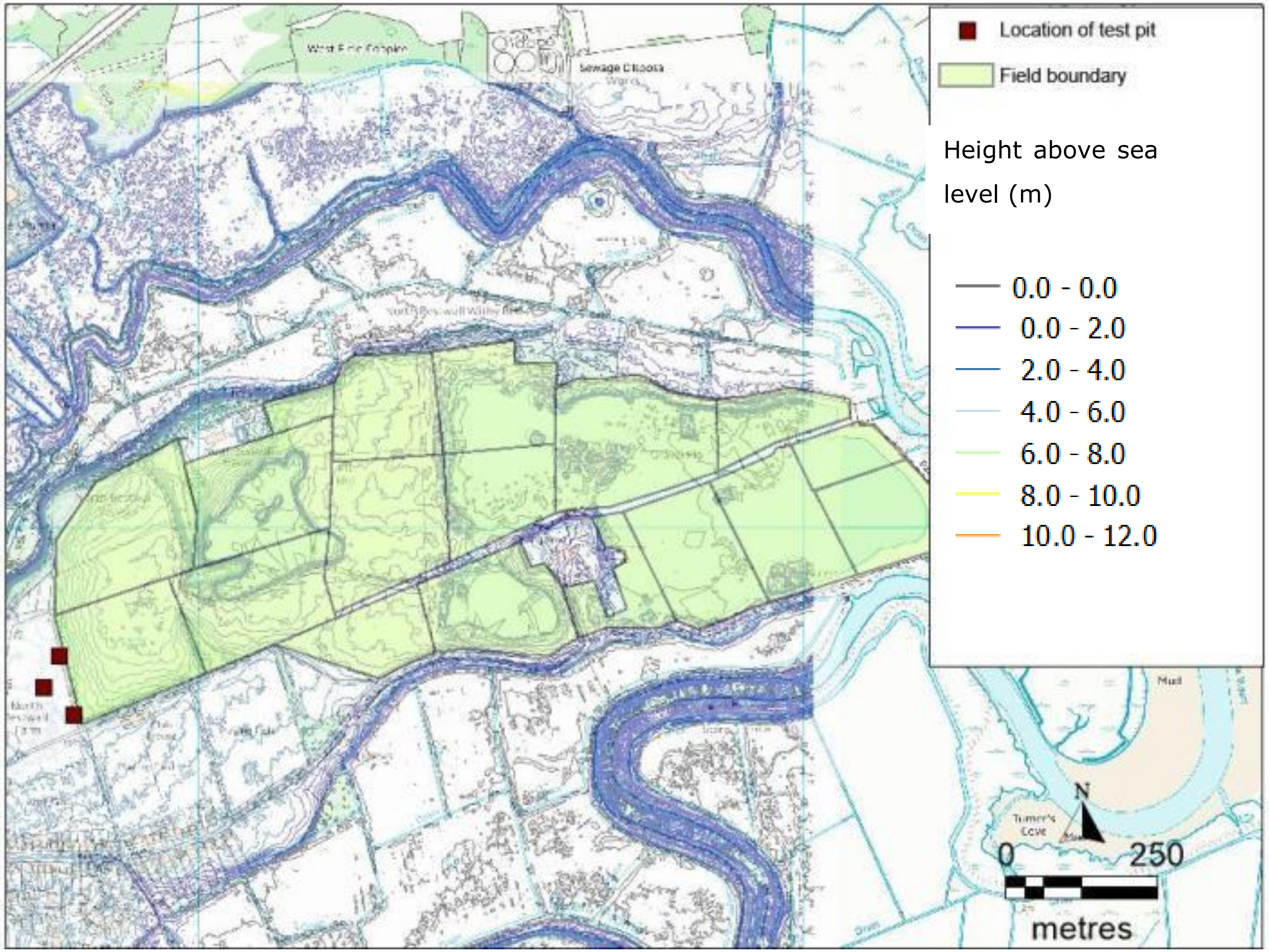


Figure 201: Map of the siege site of Wareham showing the field boundaries as they were in 1992 prior to gravel extraction. Base map Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. ©LIDAR provided by data.gov.uk (Environment Agency 2018).

7.4. Historic land use assessment

A land use assessment was carried out to consider its usage over the past two centuries (tables 68 and 69). The priority was to identify periods of arable and periods of pasture use to address how long fields have been under the plough. As bullets were not given individual find spots, spatial analysis cannot be conducted and so a field by field land use assessment was not carried out for this site.

Land use	Source (maps and aerials)	Date
South and eastern fields under arable (north not surveyed)	Scott estate map (DHC/D/DAS/4739) (Ladle 2012)	1823
All arable apart from NE corner pasture	Tithe map (East Stoke tithe map 1844)	1844
All arable apart from top NW corner and SE corner which are pasture	Land Utilisation Survey of Britain (Ordnance Survey of England and Wales 1935)	1935
All arable, northern field pasture, SE corner pasture	(Aerial photograph RAF/CPE/UK/1821 1946)	1946
All fields in arable cultivation apart from two in top NW corner	(Aerial photograph RAF/58/2775 1959)	1959
All arable	(Aerial photograph RAF/39/3812 1971)	1971
All arable	("Aerial photograph OS/82032/179" 1982)	1982
Arable with quarry lakes	(Aerial photograph SY 9287/12 NMR 18133/15 1998)	1998
Grassland and quarry	Field observations	2016

Table 68: Land use assessment of Wareham siege site.

Land use	Source (maps and aerials)	Date
Arable	(Ordnance Survey of England and Wales 1935)	1935
Arable	RAF/CPE/UK/1821	1946
Arable	RAF/58/2775	1959
Arable	RAF/39/3812	1971
Arable (new boundary of trees in place splitting the field in two- survives to present day)	OS/82032/179	1982
Pasture	SY9287/8 NMR4730/47	1992
Pasture	SY9287/12 NMR18133/15	1998
Pasture	Field observations	2016

Table 69: Land use assessment of field sampled for soil.

The site of Wareham lies in an agricultural landscape which has been farmed for centuries. Research suggests that the western end of the site was under cultivation for the majority of the medieval period, though there is no documentary evidence to support this (Ladle 2012, 324). By the parliamentary enclosures in the 17th century the landscape was a mixture of arable and pasture, and by 1823 an estate map of the southern extent of the site denotes all fields are under arable cultivation. The majority of pasture was confined to the banks of the river to the north and south of the current study area (Ladle 2012, 327). By the time of the land utilisation survey of Britain in the 1930s the majority of the fields were under arable cultivation, bar some of the northern and eastern fields (figure 202).

The majority of the landscape under investigation has been under arable cultivation since the early 19th century and the vast majority of the site remains under the plough until the site was destroyed in the early 1990s by gravel extraction. The majority of field boundaries present in 1992 were well established when the tithe survey was conducted in 1844 (East Stoke tithe map 1844). The site now forms an area of large shallow lakes and sloping grassland.

The field to the west of the siege area where the three test pits were dug has been under arable cultivation for a similar time period to the rest of the landscape and resides in the same topography and superficial geology. It is only since quarrying activity started at this location that the field has been converted to pasture and should therefore provide reliable background soils data for the rest of the siege site.

7.5 Lead bullet condition assessment

280 bullets from Wareham were assessed for their condition using the methodology laid out in section 3.4 and appendix I. This equates to 50% of the total bullet collection from the site. The bullets exhibit variations in condition, with 28% scoring a 2, 48% scoring a 3 and 22% scoring a 4 (figure 203). Only 2% of the collection scored a 1 for very good condition, highlighting the lack of good preservation at this site. 80% of the collection scored a total between 9 and 14 out of a possible 20, highlighting that the collection generally edges towards fair to poor condition (figure 204). An explanation of how overall condition equates to the five conditions category score is presented in table 70.

97% of the collection scored a 1 or 2 for preservation of shape, reiterating what was observed in the other site assemblages that lead bullets suffer little in terms of shape alteration in the ground. The most intriguing condition category result is the smoothness of surface, which increases in number of bullets for each condition score; 70% of the collection scored a 3 or 4 for smoothness of surface indicating the dominance of rough uneven surfaces (figure 205). Stability of surface also scores high, with 72% of the collection scoring a 3 or 4 for condition, indicating that a vast proportion of the collection has degraded, damaged or lost patina. Surface detail does not score as highly as the previous two categories, though 42% still score a 3 or 4. Surface detail can still be identified on a number of bullets which have also suffered deterioration (figure 206), though on some bullets degradation is too severe to identify surface marks (figure 207).

It is evident from the five condition category assessment that few bullets score 1 for very good condition in any category apart from preservation of shape; smoothness of surface scores highest in the poor category indicating that 39% of the collection has poor surface preservation and rough surface textures.

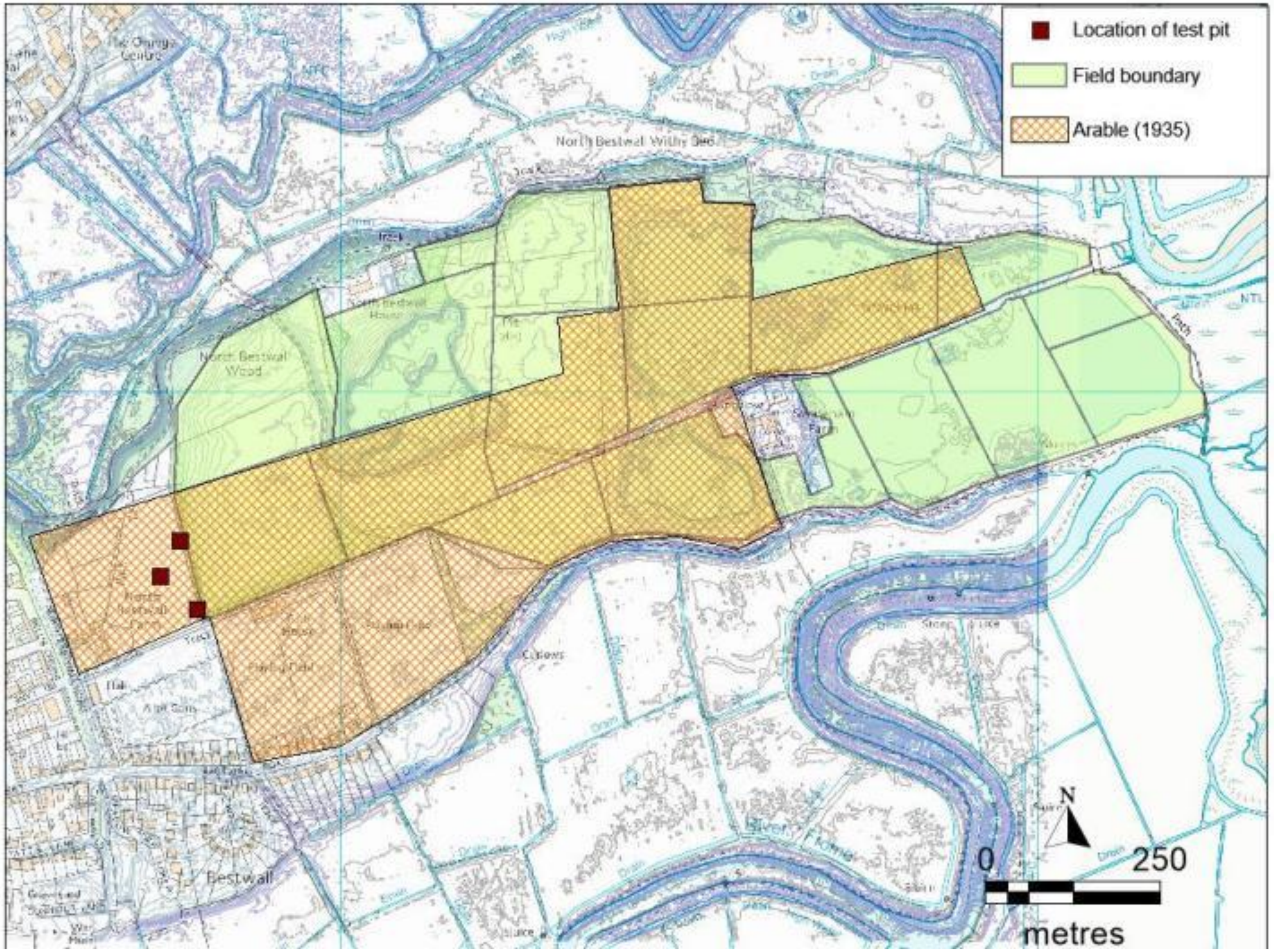


Figure 202: Map of Wareham showing the extent of arable cultivation in 1935. All fields are under arable by 1971. Base map Mastermap 1:1000 ©Ordnance Survey EDINA Digimap Ordnance Survey Service. .©LIDAR provided by data.gov.uk (Environment Agency 2018).

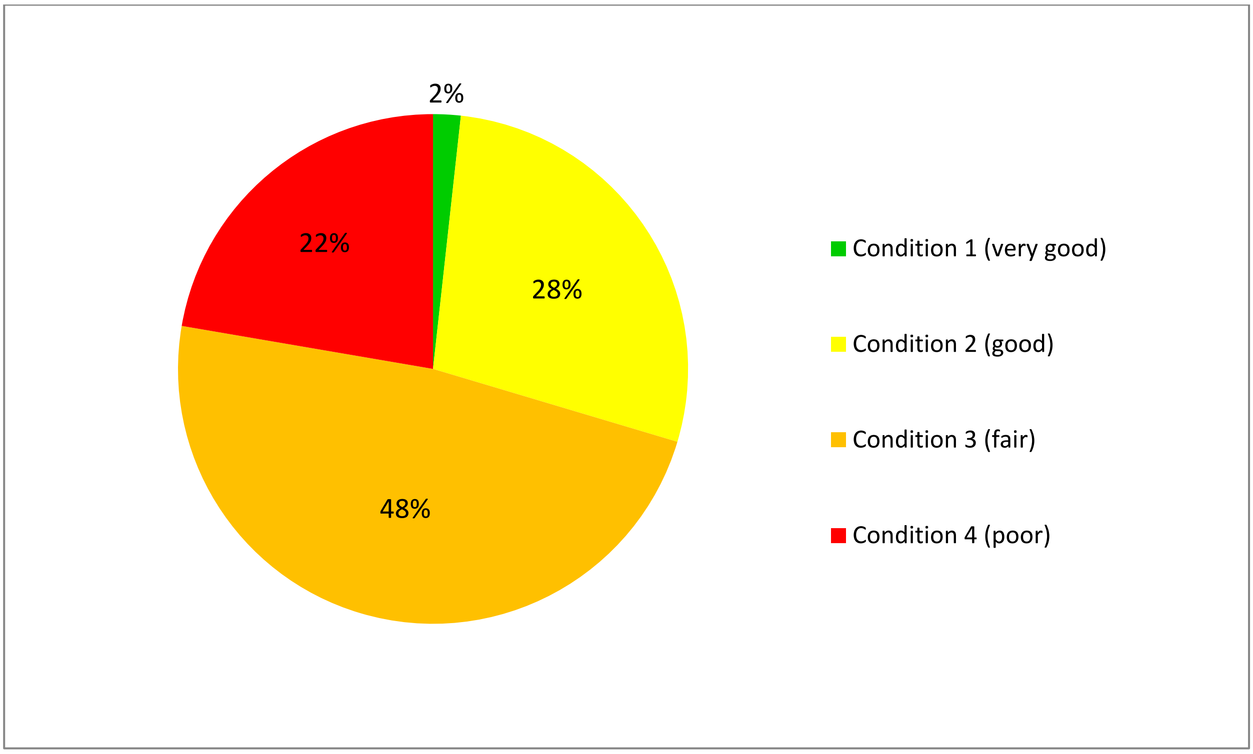


Figure 203: Overall condition of bullets from Wareham by total percentage of collection studied.

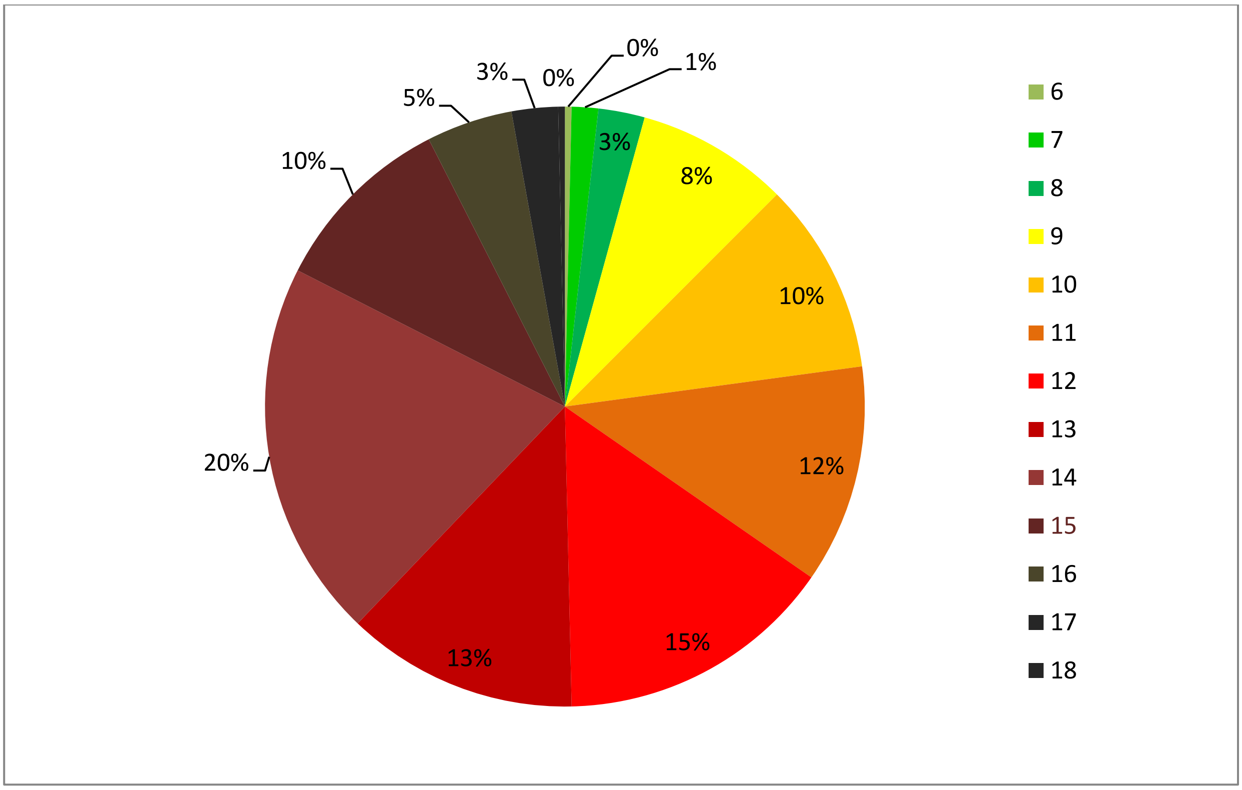


Figure 204: Total scores of lead bullets from the 5 condition categories (out of a possible 20) by total percentage of collection studied. The colours equate to the same scoring ranges as the overall condition score in figure 204).

Condition score	Overall score of lead bullet condition (possible total 4)	Total condition score from 5 condition categories (possible total of 5-20)
Very good	1	5-7
Good	2	8-10
Fair	3	11-13
Poor	4	14+

Table 70: How the overall condition score equates to the total category condition score of lead bullets.

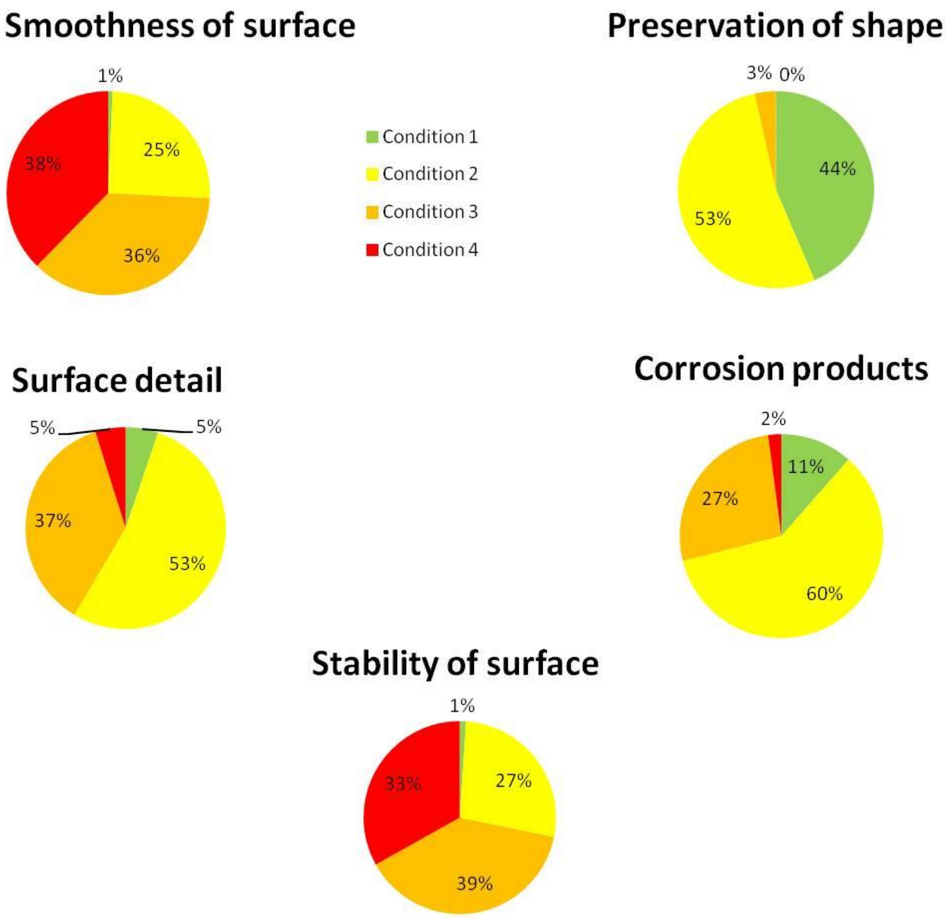


Figure 205: Results of lead bullet scores on all 5 categories of condition assessment.

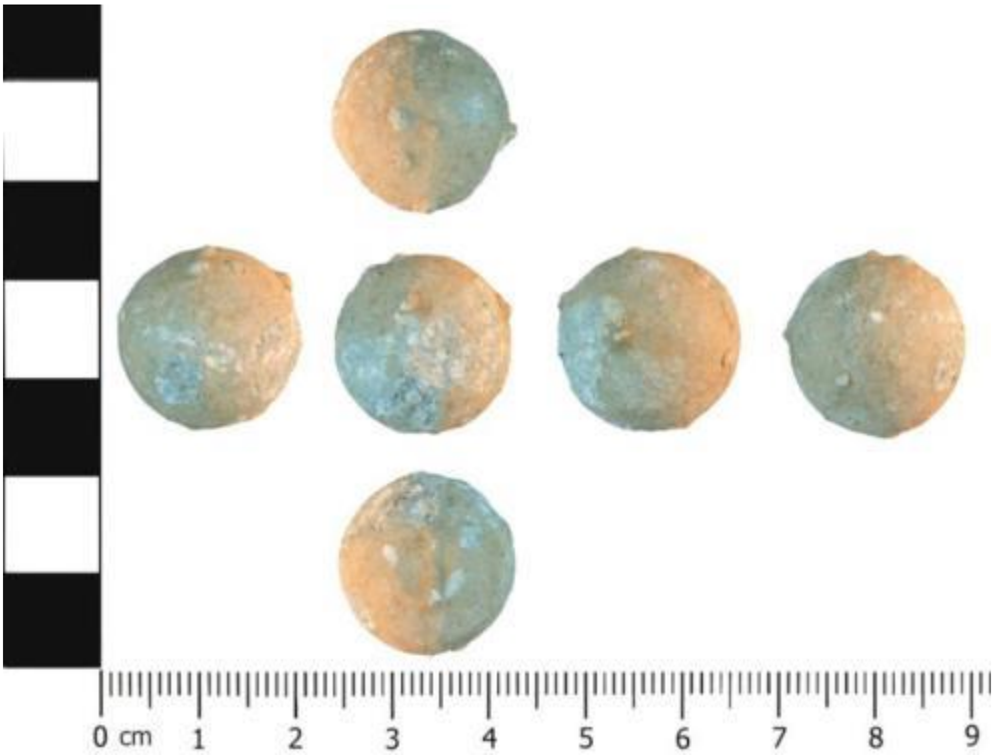


Figure 206: Bullet with severe localised corrosion, pitting and loss of surface, but still with clear cut sprue mark (WAR 2250).

Figure 207: Bullet from Wareham showing severe degradation of surface and lack of identifiable surface details (WAR2122).

Further data was collected on certain corrosion attributes, the results of which can be seen in table 71. The three categories which stand out as scoring high are localised corrosion, abraded surfaces and powdery surfaces. As stated in section 3.3, powdery surfaces are often a sign of active corrosion triggered in the post excavation stage due to poor storage or ongoing degradation of the material and will not necessarily be due to the burial environment (Schindelholz 2001, 220). As the bullets from Wareham were initially not stored appropriately, it is highly likely they have suffered some post recovery decay.

Localised corrosion is a prevalent issue in this collection, with 52% of bullets showing severe signs of pitting or intergranular corrosion (figure 208). This may have developed due to the bullets not forming an adequate patina to protect the underlying metal from further attack. Abraded/eroded surfaces is also a common issue in this collection, with 55% of the bullets analysed showing signs of eroded surfaces, the result of which strips the overlying patina off the bullets, revealing further damaged corrosion deposits beneath (figure 209).

As discussed in section 3.3, patina breakdown often occurs in abrasive environments, where objects are in contact with abrasive sandy particles and moved around in the soil by ploughing which is a highly likely situation at Wareham due to its longevity under arable cultivation and its sandy textured soils. Some bullets are past being of archaeological use due to the severe loss of data, almost to the point of being unrecognisable as bullets (figure 210). Foard concluded that damage was so severe that accurate calibre measurements could not be retrieved from most of the collection (Foard Pers. Comm. 01.05.2017).

Corrosion, pitting and abrasion are clearly problems witnessed in this collection, though there are some bullets which are fairly well preserved and the patina has continued to preserve the metal (figure 211). Though well preserved bullets are much rarer in this collection than other sites, it does indicate that not all bullets in the collection have deteriorated. Unfortunately, as the site has been destroyed by quarry construction, no direct spatial comparison between the burial environmental and bullet find spots can be addressed.

Though cracking of surfaces does not score particularly high in this collection (8%), some are severely cracked (figure 212). This appears to be an initial intergranular corrosion process which leads to surface eruption and the surface falling away from the metal core.

Condition issue	Total number of bullets	Percentage of total collection
Hit by plough	12	4%
General pitting issues	23	8%
Significant localised corrosion	145	52%
Significant eroded/abraded surface	153	55%
Significant cracks on surface	22	8%
Powdery surface	99	35%

Table 71: Total number of bullets in collection with corrosion issues.

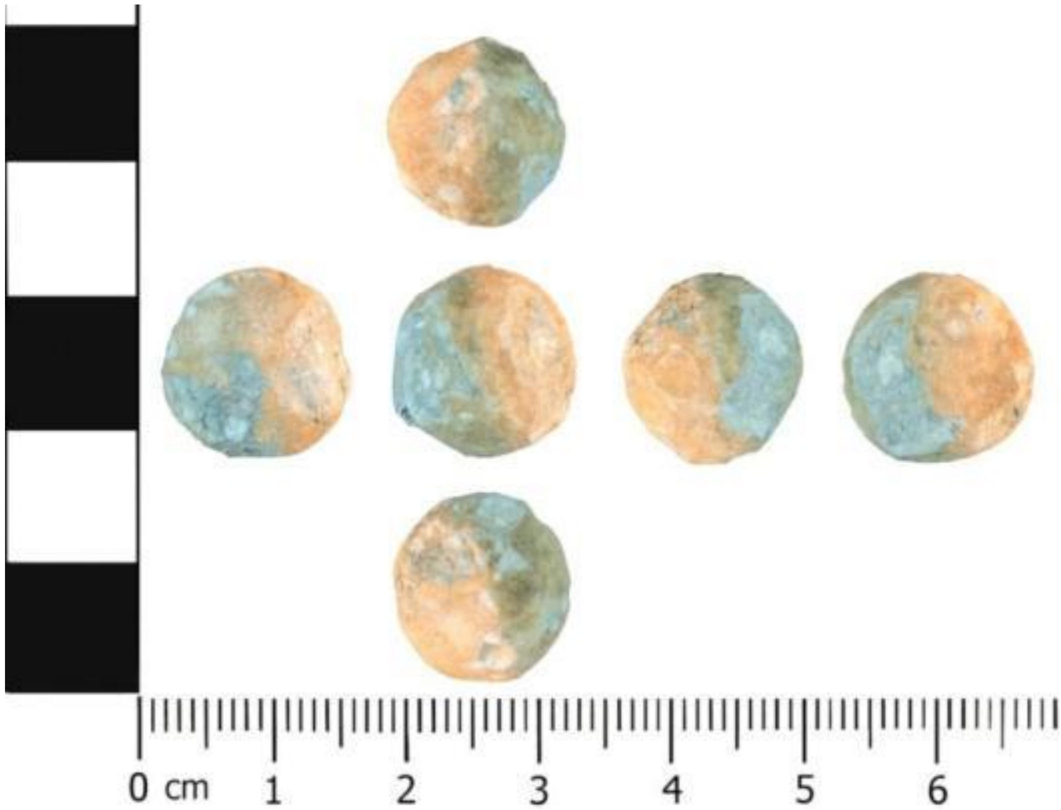


Figure 208: Bullet from Wareham with large sections of the surface and underlying metal lost to corrosion and penetrating pitting corrosion (WAR 1523).

Figure 209: Bullet from Wareham with severely eroded surface and stripped patina (WAR 2217).

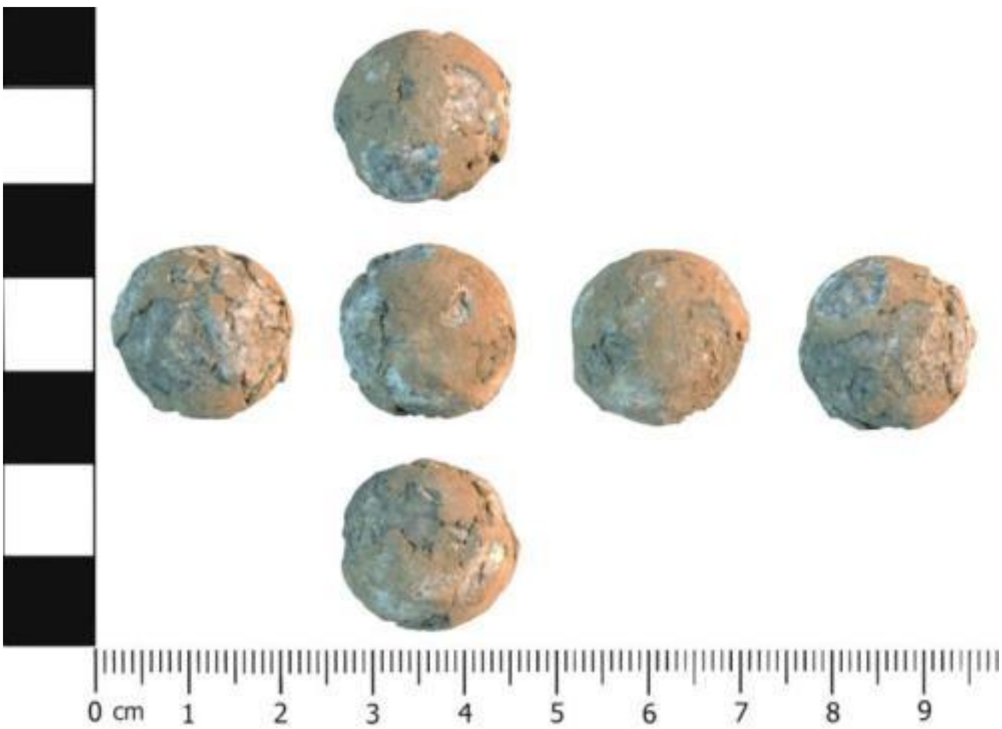


Figure 210: Extremely corroded bullet with large section of the surface crumbly away from the core, leaving the bullet almost unrecognisable (WAR 43).

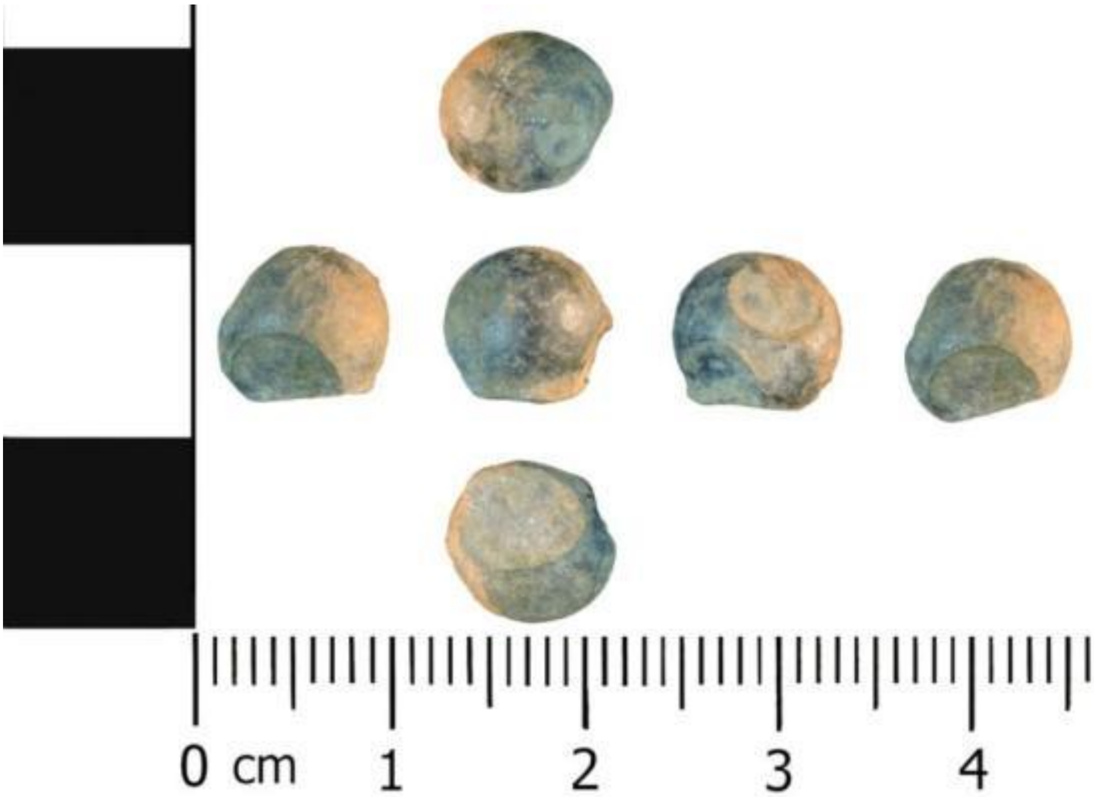


Figure 211: Well preserved bullet from Wareham with smooth patina and clear surface details (WAR 494).

Figure 212: Bullet from Wareham with severe cracking, probably developing into surface crumbling/flaking (WAR 2219).

In order to address the severity and thickness of corrosion products on the bullets, six bullets were selected to measure the patina corrosion depth. Three were selected with no abrasion or localised corrosion issues, and three with abraded pitted surfaces (table 72). A small area was scraped away and a digital microscope was used to measure the thickness of corrosion. The depth of corrosion was measured at five separate intervals and averaged.

On average bullets with abrasion and pitted surfaces had a thicker corrosion deposit, averaging at 150.25±137.07µm, with non-corroded bullets averaging at 88.33±65.27µm. This is in contrast to the bullets at Moreton Corbet, where abraded bullets have thinner corrosion deposits suggesting that thin corrosion deposits left bullets prone to abrasion, or that products had been lost in the abrasion process (section 5.5). However, due to the severity of corrosion of bullets at Wareham and the extent of corrosion penetration, this pattern does not follow with this collection. Thick corrosion deposits have formed, whilst also being abraded in the ground. Bullets at Wareham have been able to develop thick layers of corrosion deposits as a result of losing previous patina layers, which may be a continuing corrosion process as the metal continues to be lost. Edgehill showed that bullets will form fairly thin patinas, which are highly protective of surface detail, if not under stress from abrasion (section 6.5). The formation of thick corrosion layers on bullet surfaces seriously affects their value as archaeological objects as much less surface detail is available for observation.

Patinas have already being lost from the Wareham bullets, meaning the corrosion measured is likely to be a portion of the original patina (figure 213). Therefore, the measurements are likely to vary from the original patina of the bullets. It is likely that over time the bullets from Wareham have lost metal through corrosion and abrasion and formed new corrosion layers and this cycle has repeated over several decades. This process did not occur at Edgehill as their thin patinas were enough to protect the bullets in their burial environment, suggesting that the environment at Wareham is much harsher than at Edgehill.

Bullet	**Corrosion thickness (averaged from 5 measurements)**
WAR 43 (abraded, pitted), condition 4	309±87µm
WAR 866 (abraded), condition 3	74±12µm
WAR 1356 (abraded, pitted), condition 4	69±20µm
WAR 684, condition 1	163±43µm
WAR 687, condition 2	46±11µm
WAR 2219, condition 3	56±14µm

Table 72: Corrosion thickness of six selected bullets.

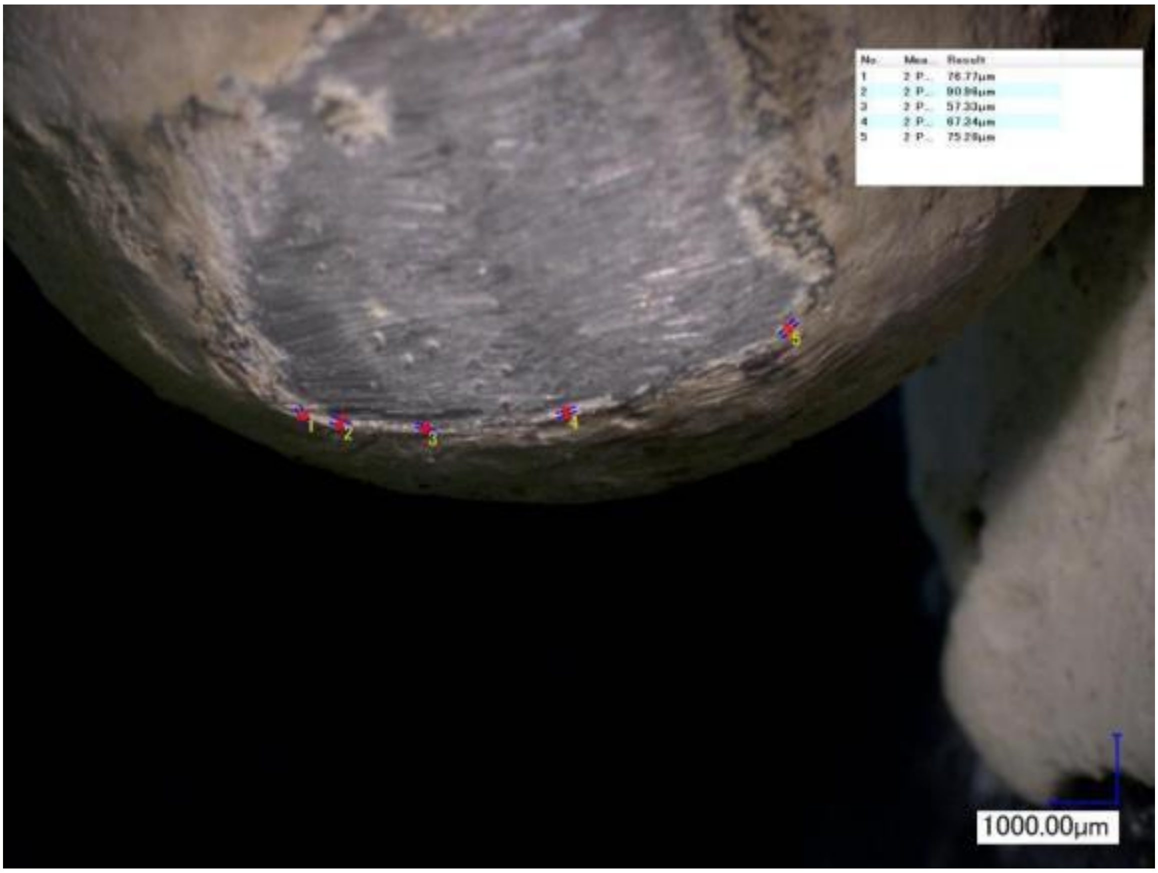


Figure 213: Example of an abraded bullet and measured corrosion thickness, revealing more than one layer of corrosion products (WAR 866).

7.6 Bullet composition and corrosion products

28 bullets from Wareham were analysed using XRF to examine their metallic compositions, as laid out in the methodology (4.5.2). The lead content ranged from 32.7% to 96.4%, with an average content of 90.2±12.1%. Tin content ranged from 0% to 63%, with an average content of 4.07±12.1%. As the graph shows, condition remains poor even when lead content is relatively high (figure 214). There is no clear pattern between the lead content of bullets and their overall preservation.

Condition of bullets did vary across the site and seven bullets were further selected to examine the corrosion products formed on the bullets. Most exhibited a range of standard lead and tin compounds on their surface (figures 215 to 228). Bullet WAR 43 contained the highest tin content at 63% and contains a mixture of lead and tin corrosion compounds in the corrosion crust. This bullet is in very poor condition with its patina in a state of deterioration and detachment from the metal. It may be that the high tin content and the formation of tin and lead compounds have allowed the bullet to deteriorate, coupled with the very acidic soil at Wareham.

The other bullets analysed exhibit a range of corrosion products and states of preservation, though the main compound formed in most cases is cerussite, which usually forms a protective layer. Bullet WAR 684 is in very good condition and has formed four different lead corrosion compounds. Bullets 687 and 866 exhibit similar patterns to WAR 684 and have formed similar products, all dominated by a layer of cerussite, but are in different states of condition. Their condition scores range from 1-3 indicating that in the majority of cases the corrosion compounds have failed to protect the underlying metal from attack.

It appears that bullets with higher tin contents which have formed cassiterite as a corrosion product are in slightly poorer condition than those which have formed lead compounds. However, regardless of corrosion product, bullets at Wareham are in poor condition compared to the other two sites. Further analysis between sites will be discussed in chapter 8.

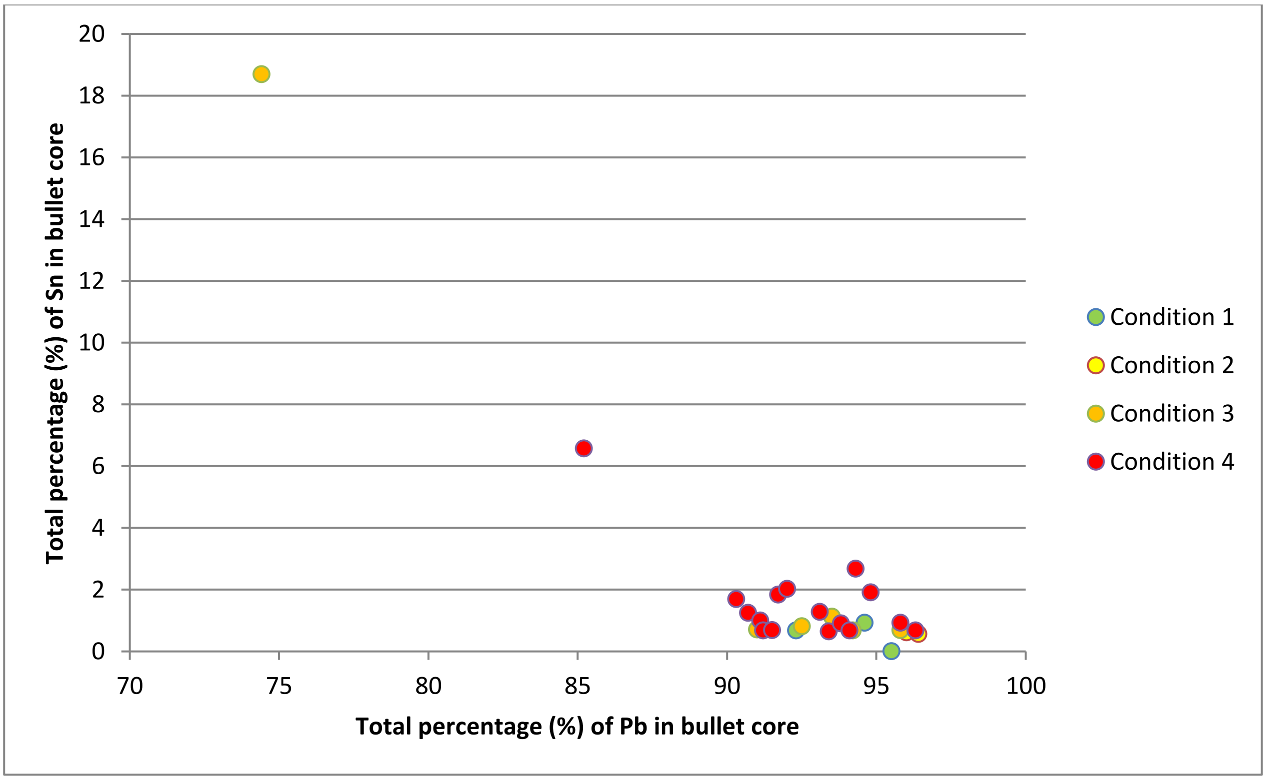


Figure 214: Lead and tin content of bullets from Wareham and corresponding overall condition scores. One bullet with a tin content of 63% has been omitted from the graph and scores 4 for poor condition. It is evident that bullets with higher tin contents are in poor condition, though bullets with higher lead contents can still score 4.

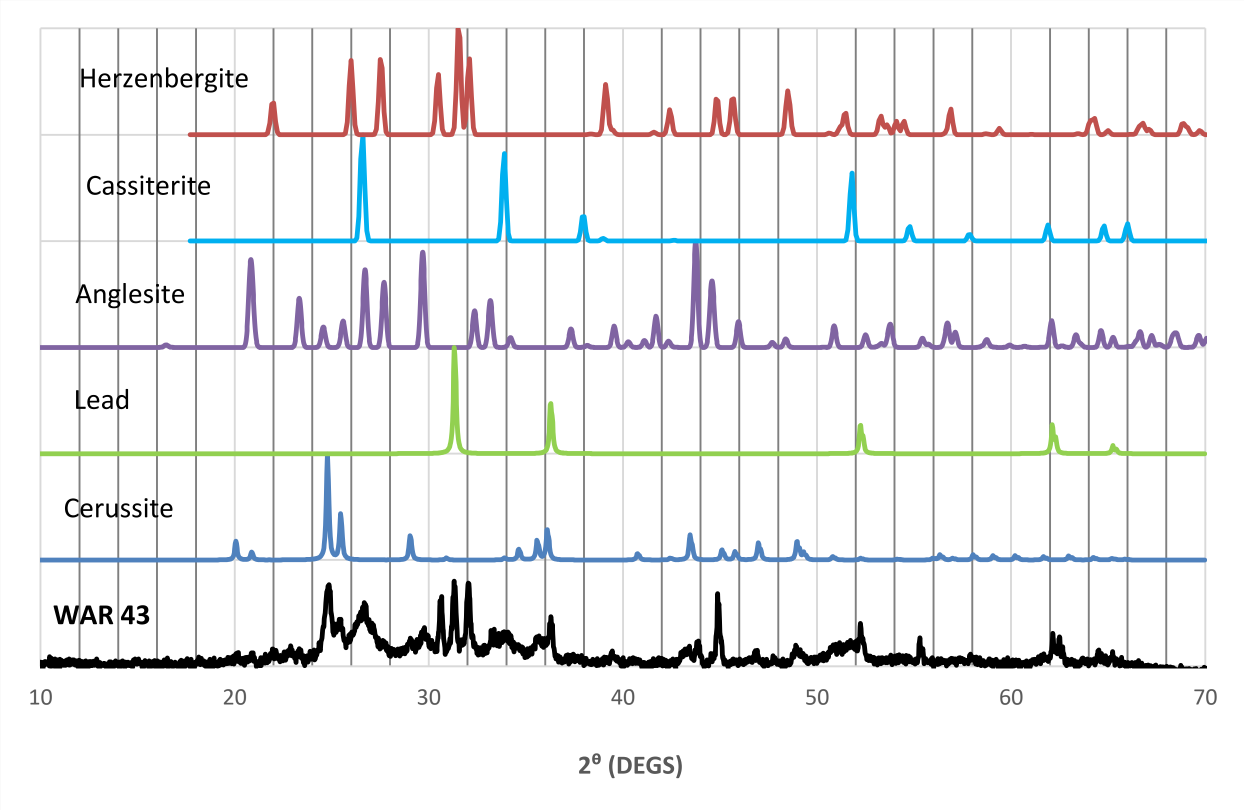


Figure 215: XRD spectra for bullet WAR 43. The main compounds present are cerussite, herzenbergite, cassiterite, and traces of anglesite and metallic lead. This bullet contains 32.7% lead and 63% tin.

Figure 216: Bullet WAR 43 with severe loss of patina, cracking and detachment of surface. Condition 4, poor.

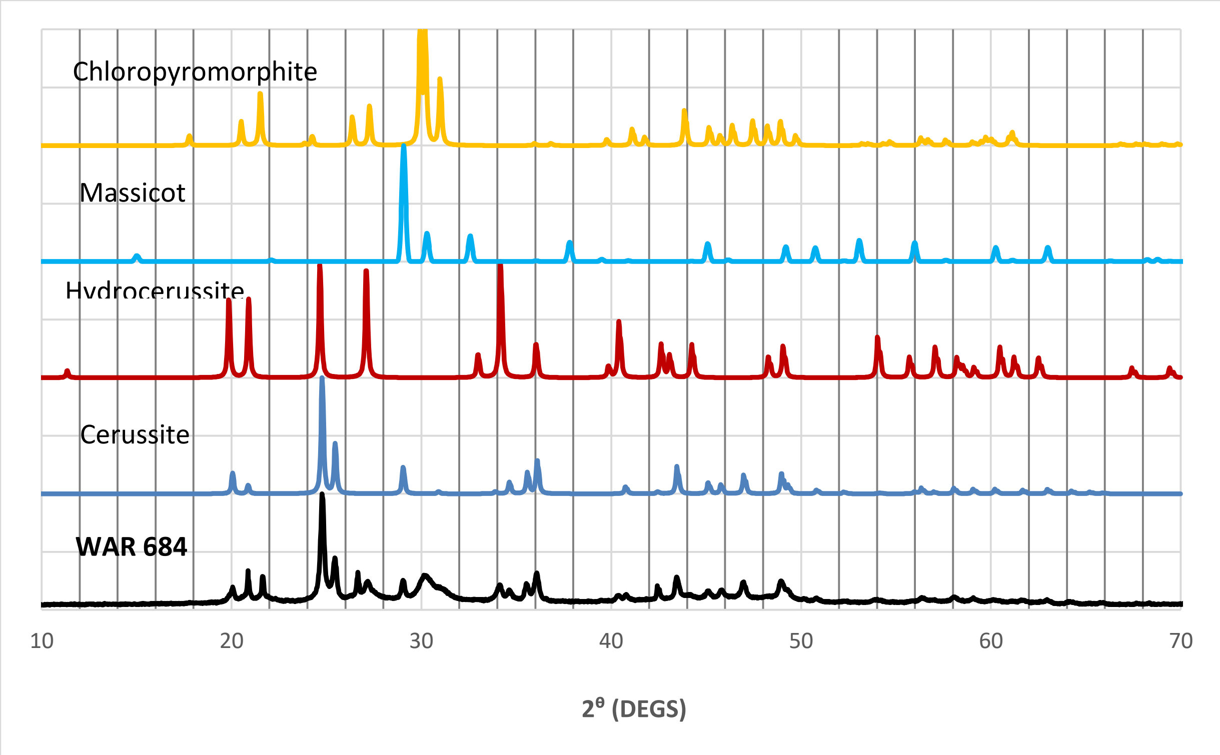


Figure 217: XRD spectra for bullet WAR 684. The main compounds present are cerussite, hydrocerussite, massicot and chloropyromorphite. This bullet contains 92% lead.

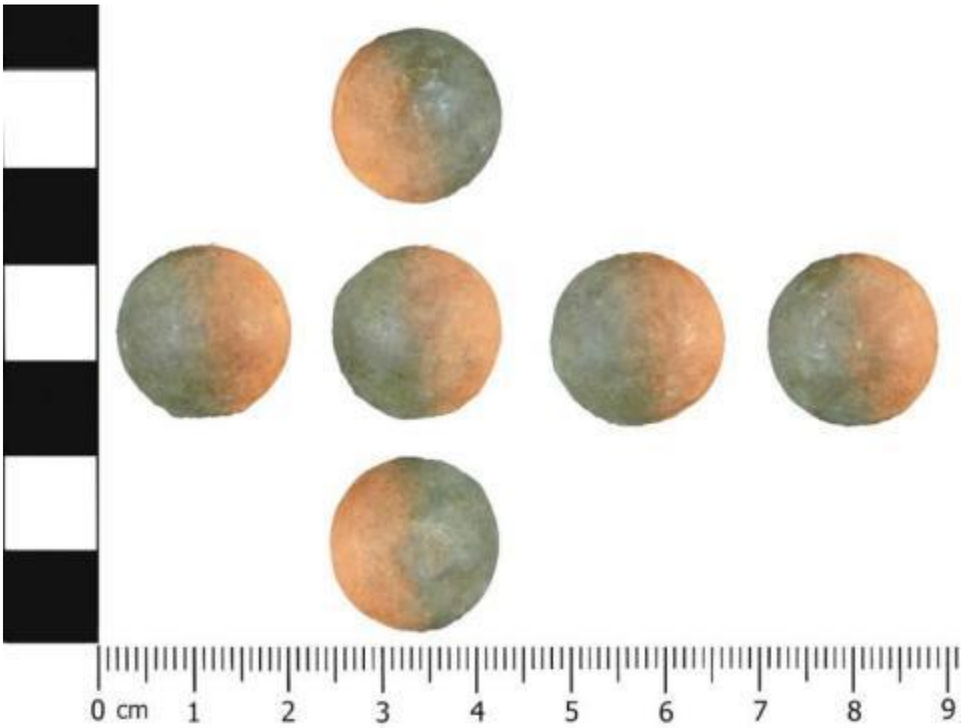


Figure 218: Bullet WAR 684 with stable smooth patina. Condition score 1, very good.

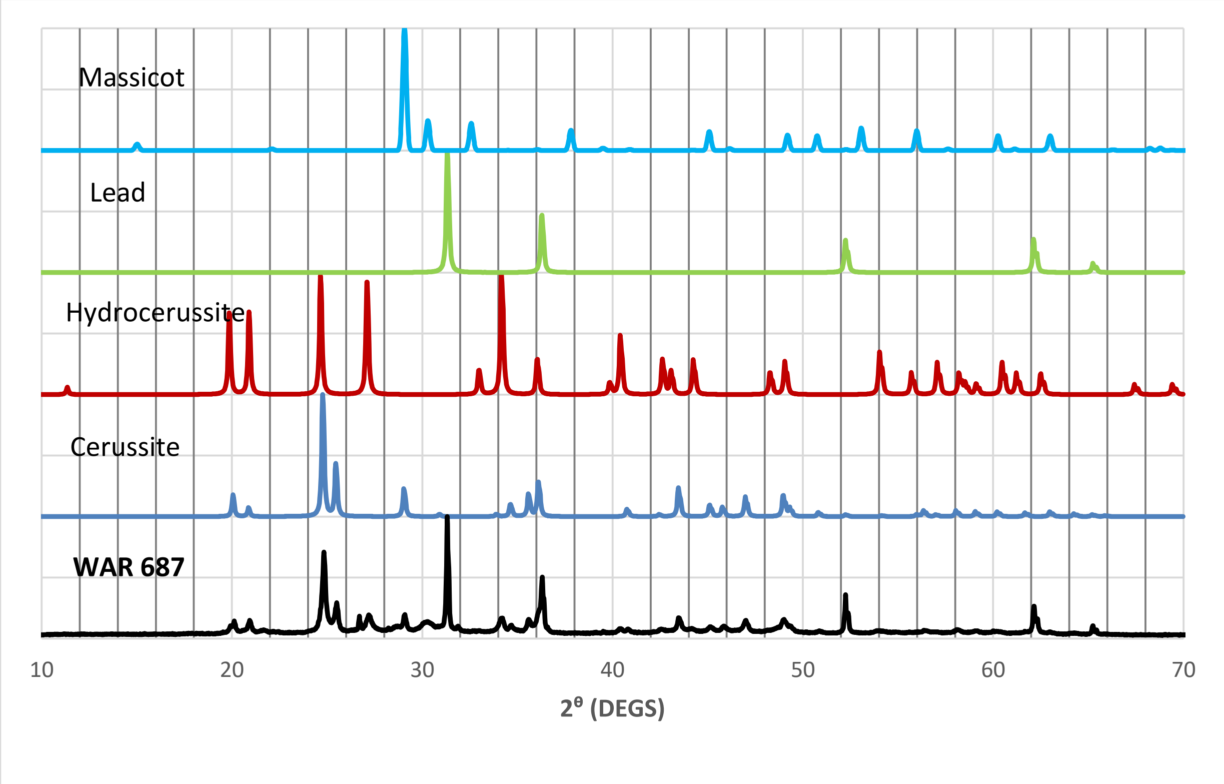


Figure 219: XRD spectra for bullet WAR 687. The main compounds present are metallic and cerussite, with traces of hydrocerussite and massicot. This bullet contains 96.4% lead.

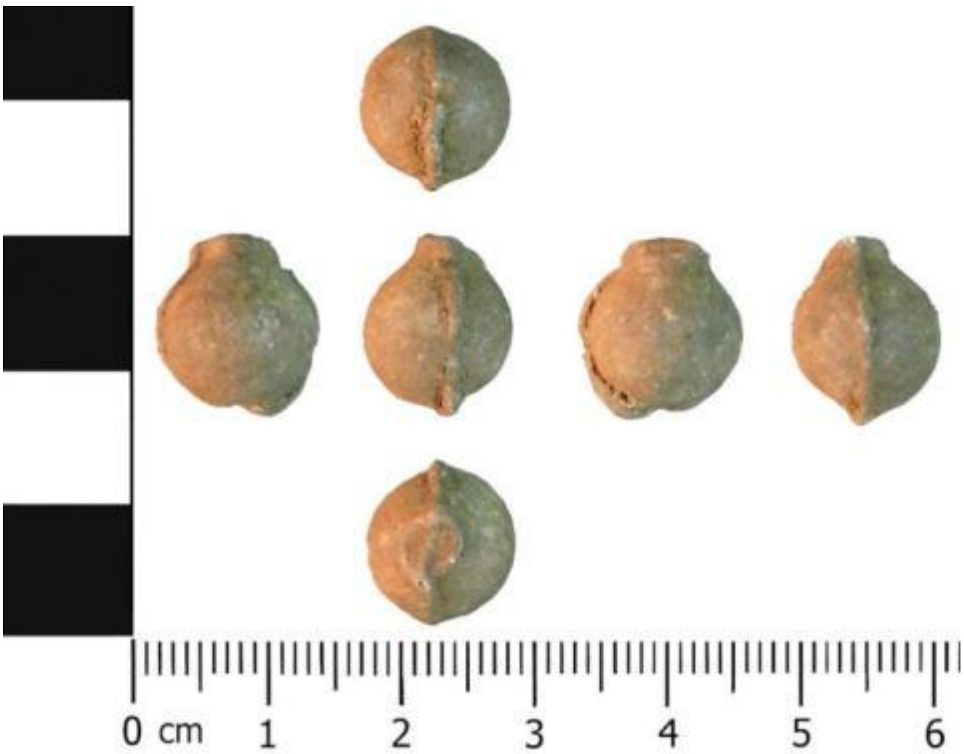


Figure 220: Bullet WAR 687 with clear surface detail and slight patina breakdown. Condition 2, good.

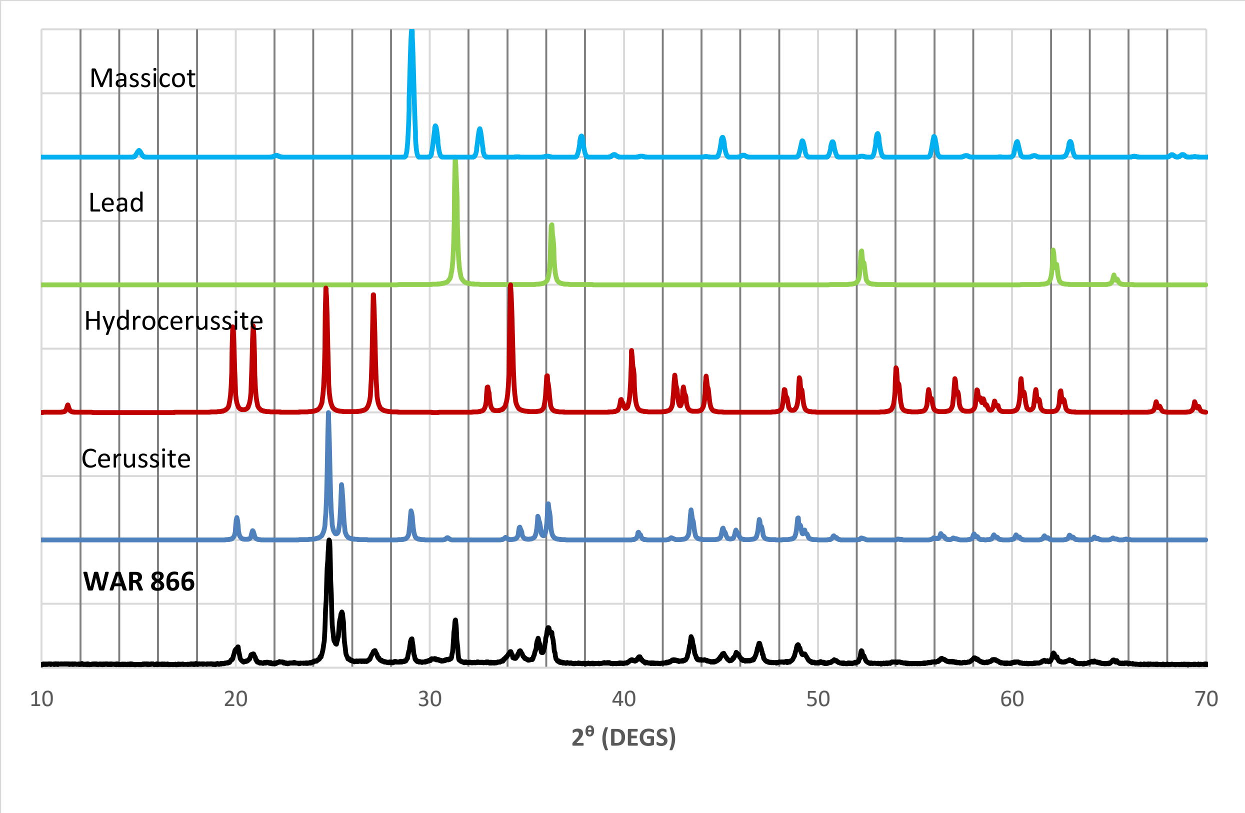


Figure 221: XRD spectra for bullet WAR 866. The main compounds present are cerussite, metallic metal, hydrocerussite and massicot. This bullet contains 91% lead.

Figure 222: Bullet WAR 866 with abraded worn surface and loss of patina. Condition 3, fair.

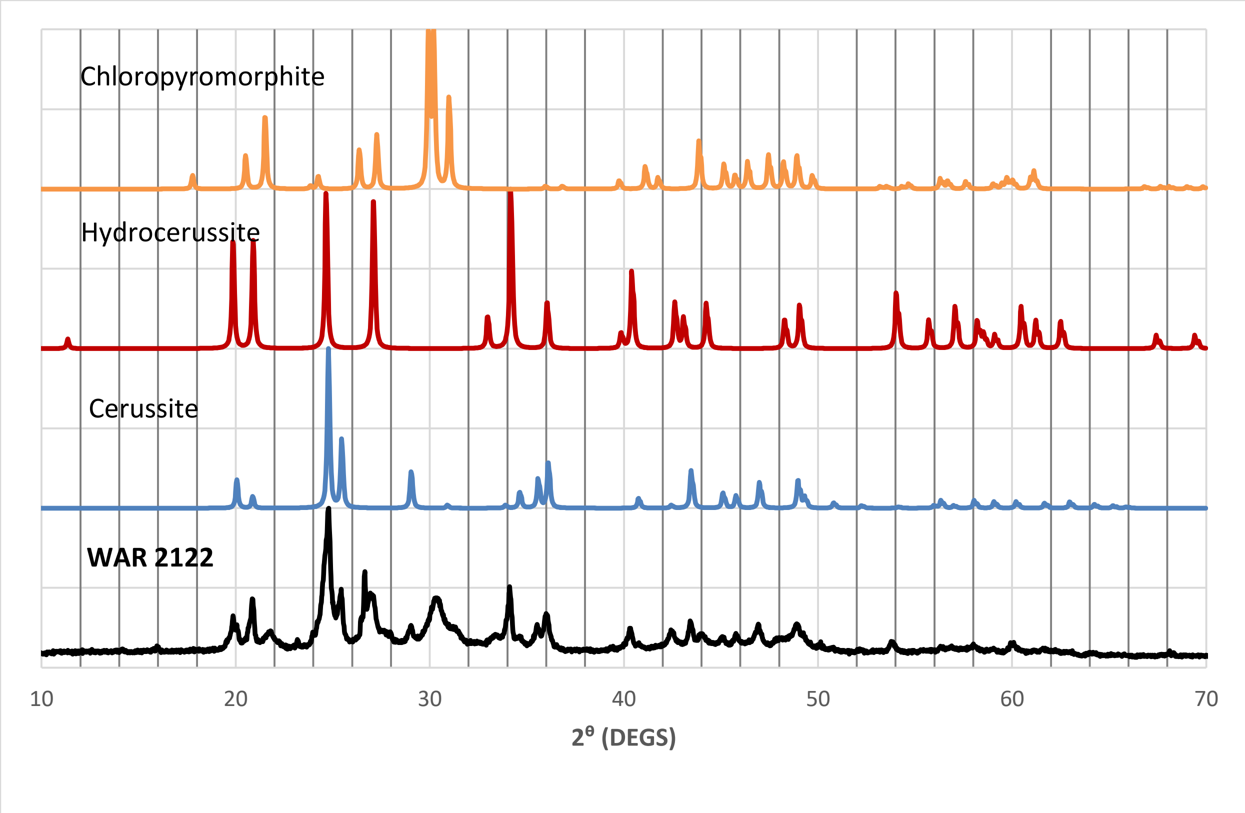


Figure 223: XRD spectra for bullet WAR 2122. The main compounds present are cerussite, hydrocerussite and chloropyromorphite. This bullet contains 92% lead.

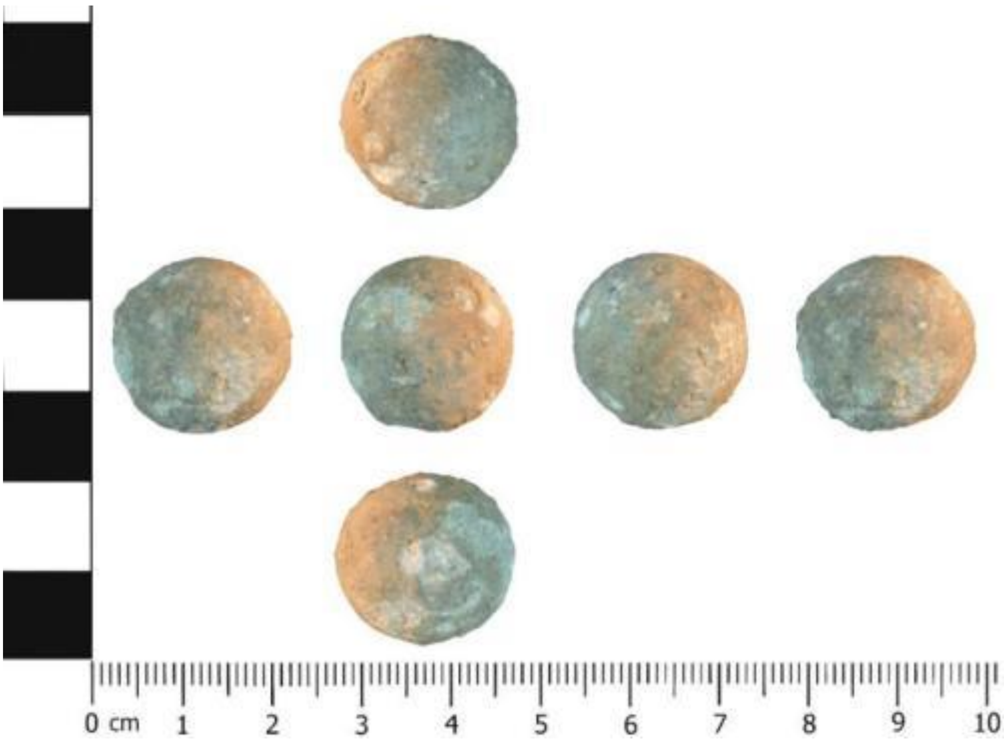


Figure 224: Bullet WAR 2122 with breakdown of patina and pitting. Condition 4, poor.

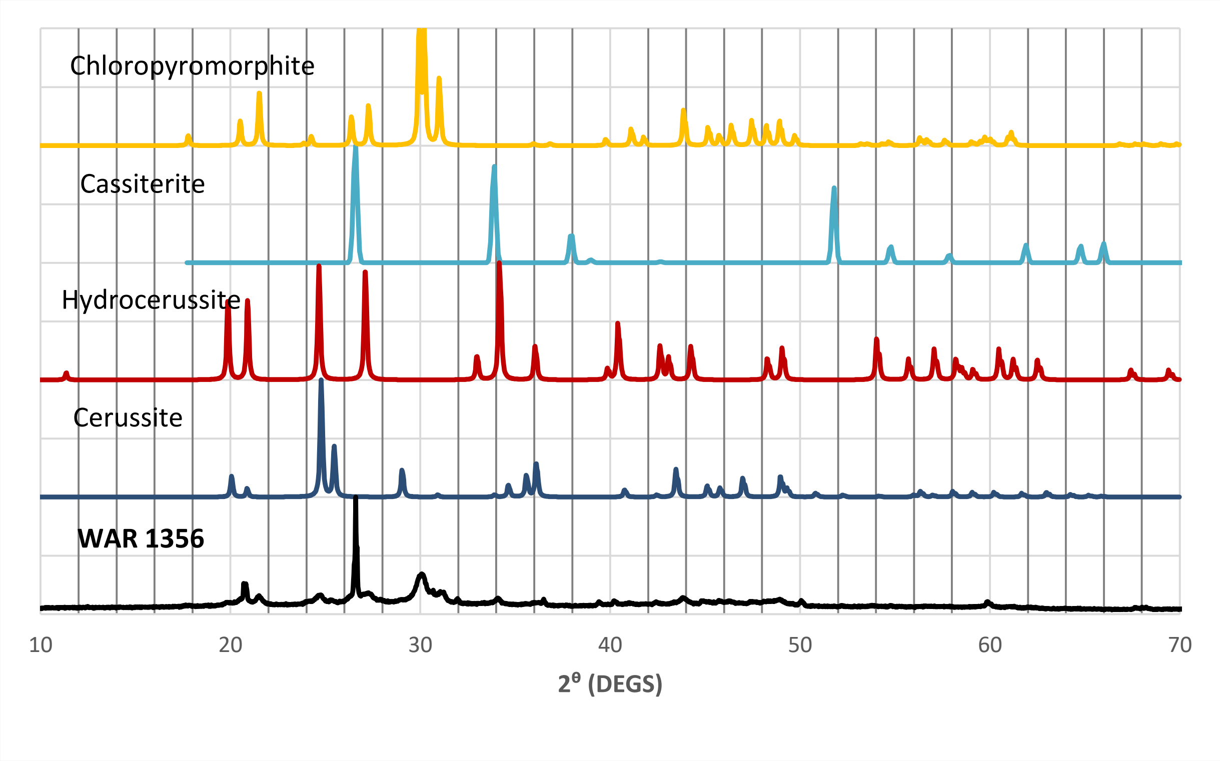


Figure 225: XRD spectra for bullet WAR 1356. The main compounds present are cassiterite and chloropyromorphite, with traces of cerussite and hydrocerussite. This bullet contains 85.2% lead and 6.57% tin.

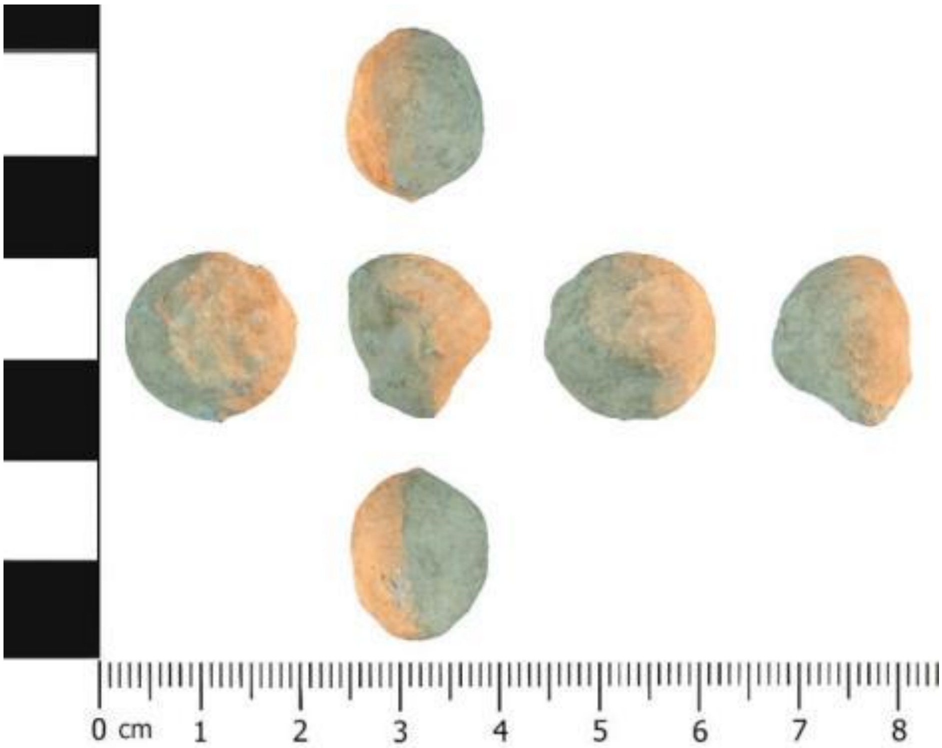


Figure 226: Bullet WAR 1356 with abraded surface and loss of patina. Condition 4, poor.

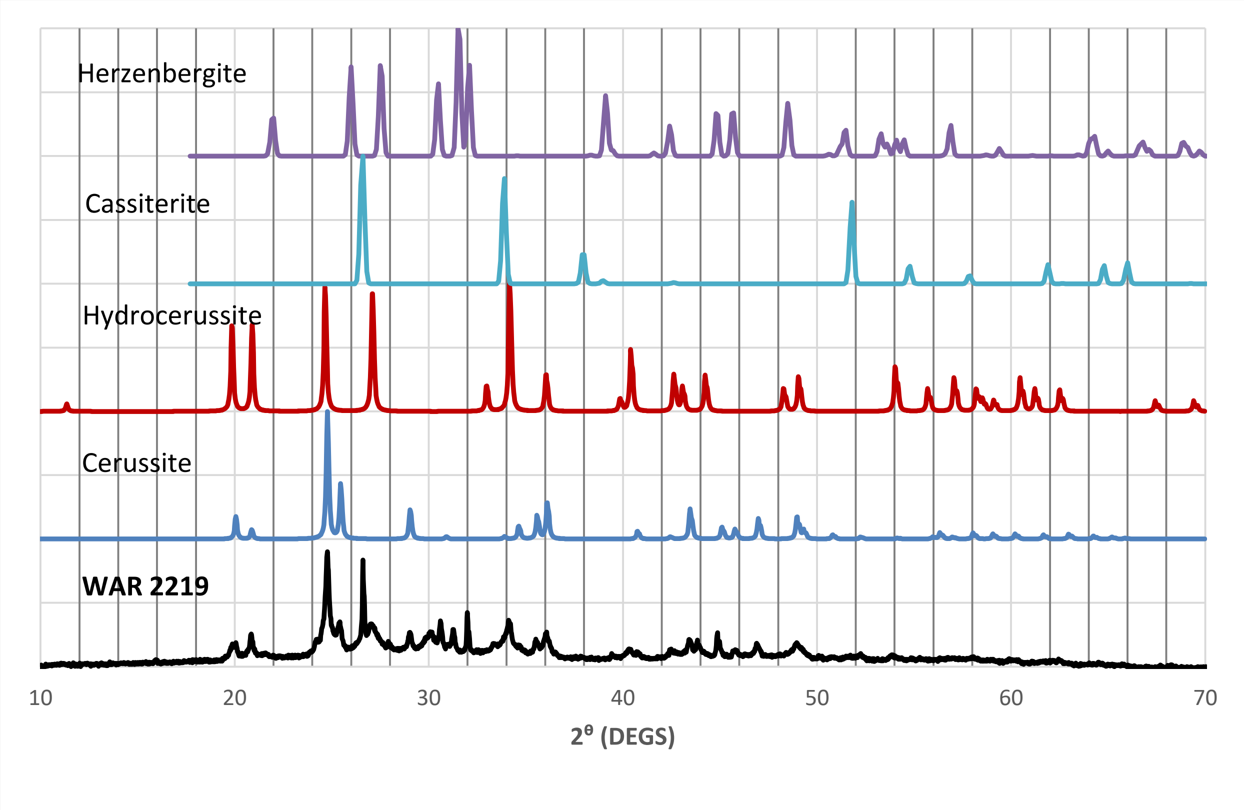


Figure 227: XRD spectra for bullet WAR 2219. The main compounds present are cerussite, cassiterite, hydrocerussite, and traces of herzenbergite. This bullet contains 74.4% lead and 18.7% tin.

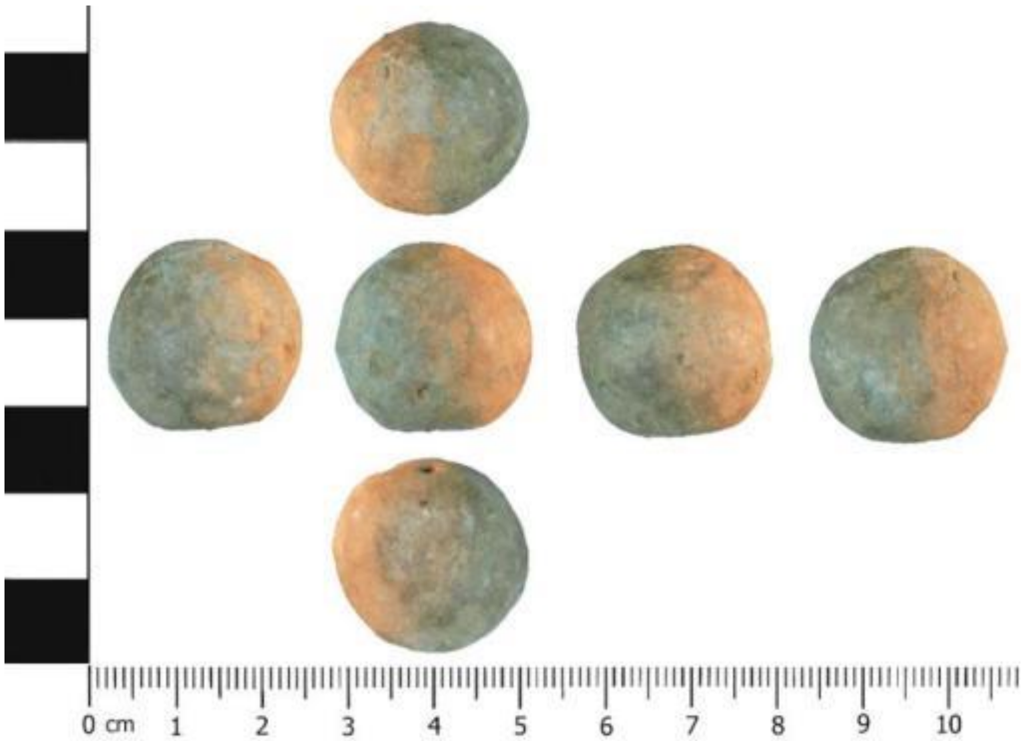


Figure 228: Bullet WAR 2219 with deep cracking and deterioration of patina. Condition 3, fair.

7.7 Soil data and bullet condition analysis

Three test pits were excavated at Wareham from as close as possible to the siege site in an area that has predominantly been under arable cultivation since at least the 19th century. Soils were extremely dry and loose upon excavation and were consistently sandy throughout the soil column, so horizons were based mainly on colour changes. The soil depths sampled are laid out in table 73. Due to the contamination of the quarry and the limited number of samples taken, statistical analysis could not be performed on the assemblage against the soil conditions.

Soil context	Soil depth range	Soil depth average
Topsoil	0.30-0.40m	0.34m
Subsoil	0.50-0.60m	0.53m
Lower subsoil	0.70-0.90m	0.77m
Natural	0.85-1.10m	0.93m

Table 73: Recorded soil contexts and corresponding depths.

7.7.1 pH results

pH ranges from 4.46 to 5.84 $CaCl_2$ (5.63 to 6.79 H_2O) throughout the soil column, with pH increasing slightly with soil depth (figure 229). Topsoil pH ranges from 4.46 to 4.72, subsoils from pH 5.21 to 5.4, lower subsoils from pH 5.55 to 5.66, and deepest natural deposits from 5.41 to 5.84. Though pH does increase slightly down the soil column, all measurements taken were acidic, with topsoils the most acidic averaging at 4.56±0.14.

This level of acidity in the topsoil is particularly dangerous for the preservation of metal; anything below pH 4.5-5.5 will seriously increase the ability of patina layers to become soluble and dissolve (Costa and Urban 2005, 50; Goodwin 2006, 771). In acidic solutions oxidation occurs with hydrogen ions rather than oxygen ions, forming soluble rather than insoluble corrosion products. This may explain the poor preservation of the bullets at Wareham; some may have failed to form an effective protective patina initially, leaving the metal prone to continuing corrosion. The severity of the acidity is a concern, as in aerated soils with a positive electrode potential (as most topsoils will have), pH of around 4.5 will shift lead from being in a passive state to an active state of corrosion (Turgoose 1985, 22). If the pH has been at such levels for prolonged periods it is likely the lead bullets have been actively corroding in the ground.

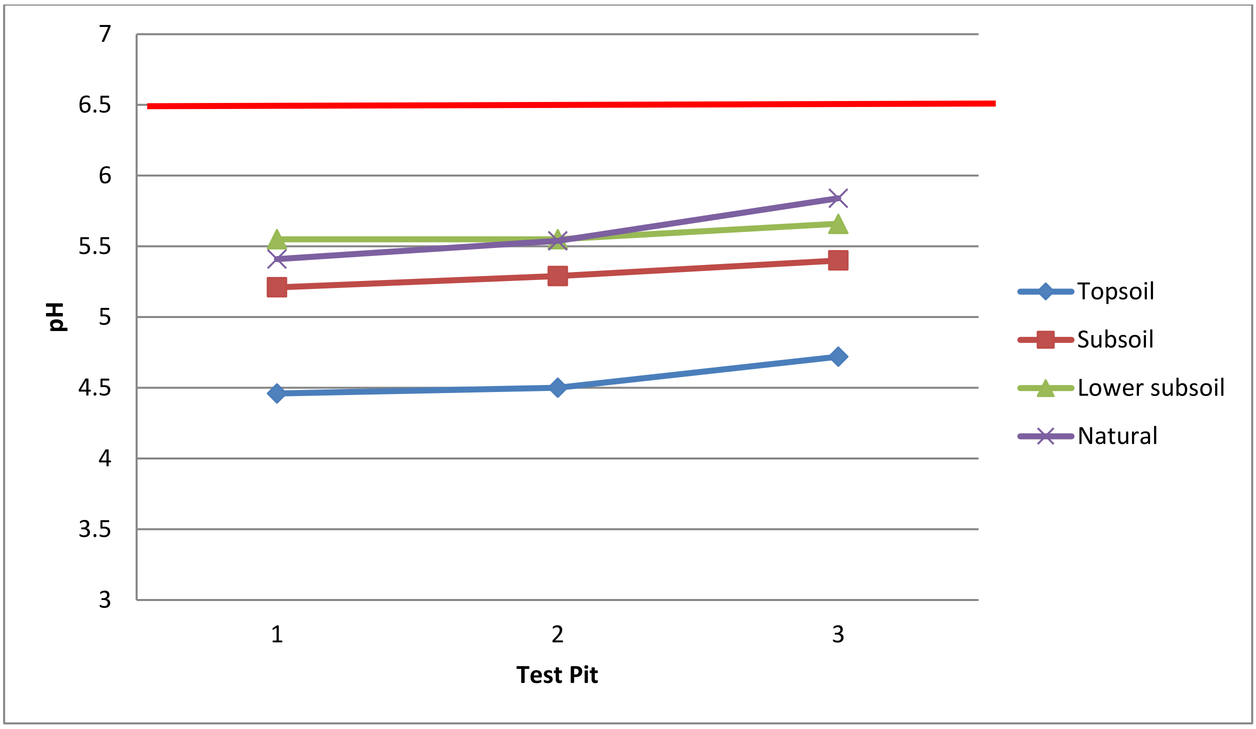


Figure 229: pH of all soil layers and samples from Wareham. The red line represents the pH level in a neutral soil.

7.7.2 Conductivity results

Conductivity levels from the site were very low, ranging from 7.91μS/cm to 17.84μS/cm. The highest levels of conductivity were recorded in topsoil deposits, averaging at 15±3μS/cm though this is still extremely low (figure 230). The lack of conductivity is due to the nature of the soil and the conditions at the time of sampling. The soil has a very high sand content which provides very efficient drainage through the soil column. The very dry conditions at the time of sampling also meant very little water was present in the soil column, which will account for the lack of conductivity. In terms of soil corrosivity, these conductivity levels are insignificant and would not promote the corrosion of metals.

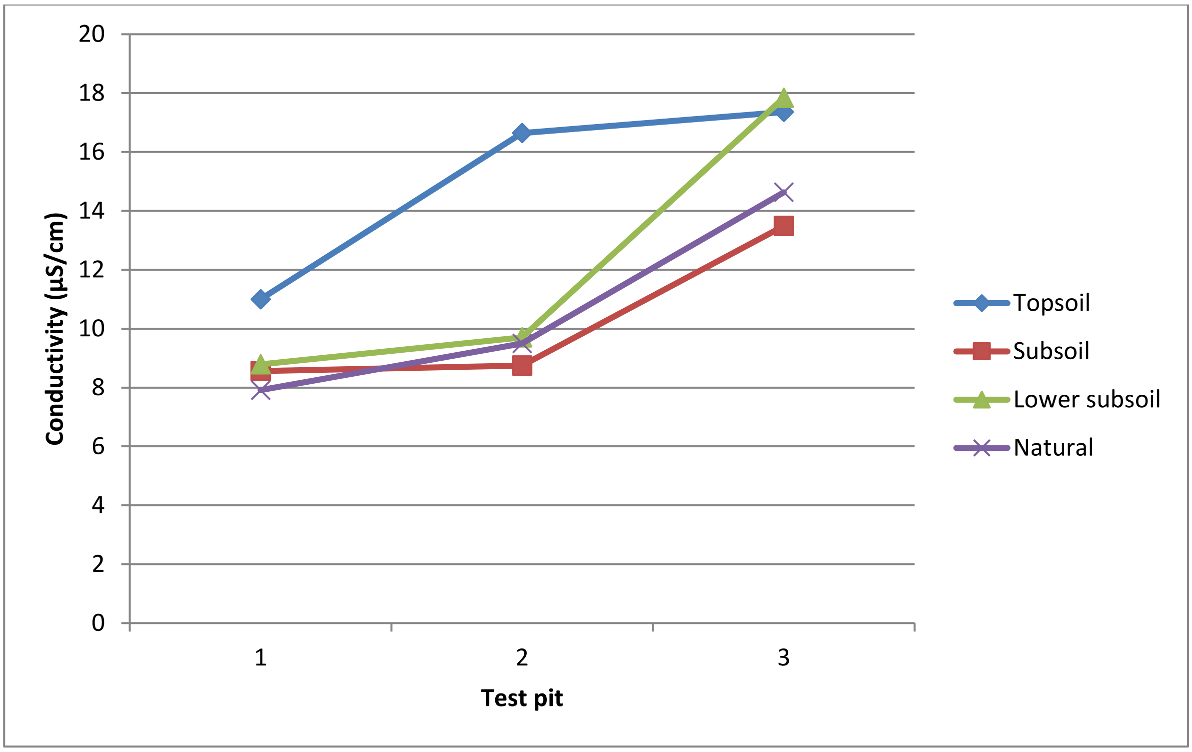


Figure 230: Conductivity readings for all soil contexts from Wareham.

7.7.3 Water content results

Water content ranges from 1.78% to 10.29%, with highest readings in topsoil deposits. Topsoils range from 8.43% to 10.29%, with much lower levels in subsoil deposits (figure 231). These very low water contents are explained by the soil texture of loose sands which do not have an effective water holding capacity and drain incredibly quickly. Water content above 20% should be deemed an aggressive soil (see section 2.3.3.6).

However, even though the high sand content does not allow a high water holding capacity, it does allow the rapid movement of water through the soil column. Sand-based soils contain large soil particles and large pore spaces which allows a higher amount of water and oxygen to flow through them. Leaching of corrosive substances such as acid precipitation and fertiliser salts is also faster in well drained soils. This is the opposite of clay based soils where oxygen deficiency can reduce the rate of corrosion (Gerwin and Baumhauer 2000, 74-76). The rate at which water passes through the soil profile at Wareham is likely to increase the rate of corrosion of lead.

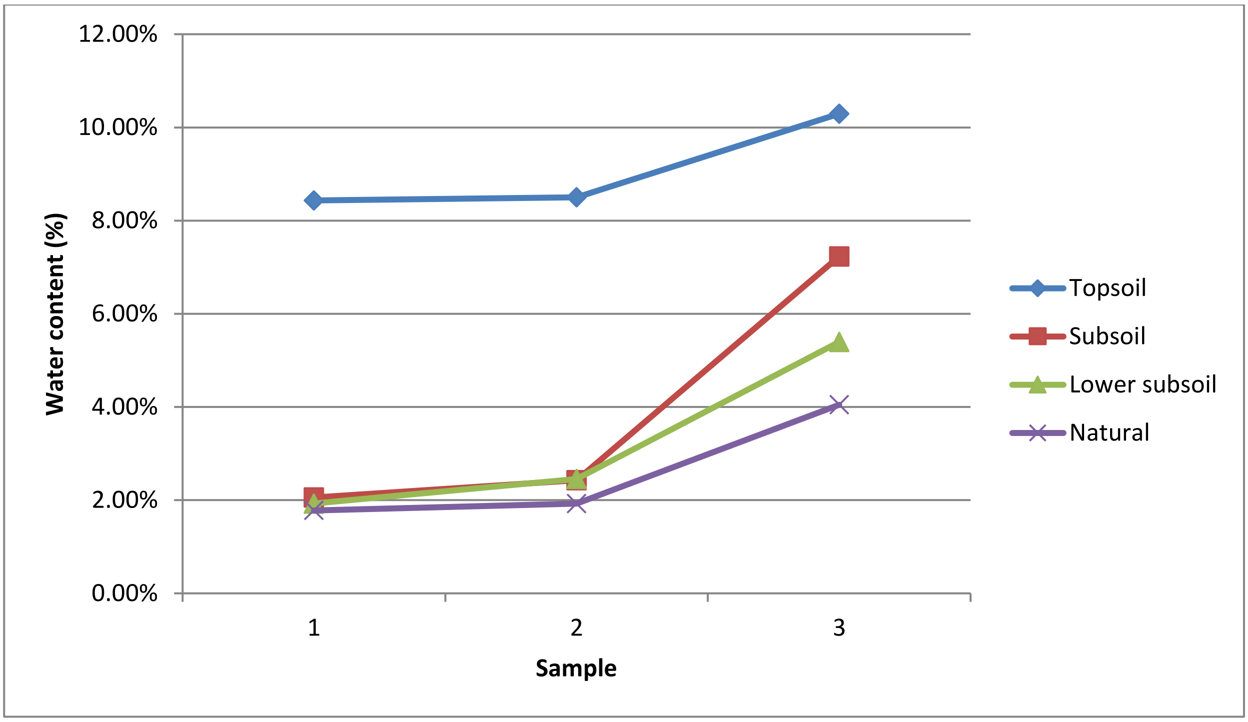


Figure 231: Water content of soil samples from Wareham revealing low levels.

7.7.4 Organic content results

Organic content readings in all soils were very low, ranging from 1.04% to 3.71%. This indicates that the soils are not organic soils and there is very little organic content throughout the soil column (figure 232). To be an organic soil a content of 15-25% would be expected, indicating that Wareham soils are very low in organic content. Soils with an organic content of 10-20% or above should be deemed aggressive towards metals and these samples recorded from the quarry are almost void of organic matter. This lack of organic matter is partly a result of the soil texture as sand particles do not bind and hold on to organic particles very easily.

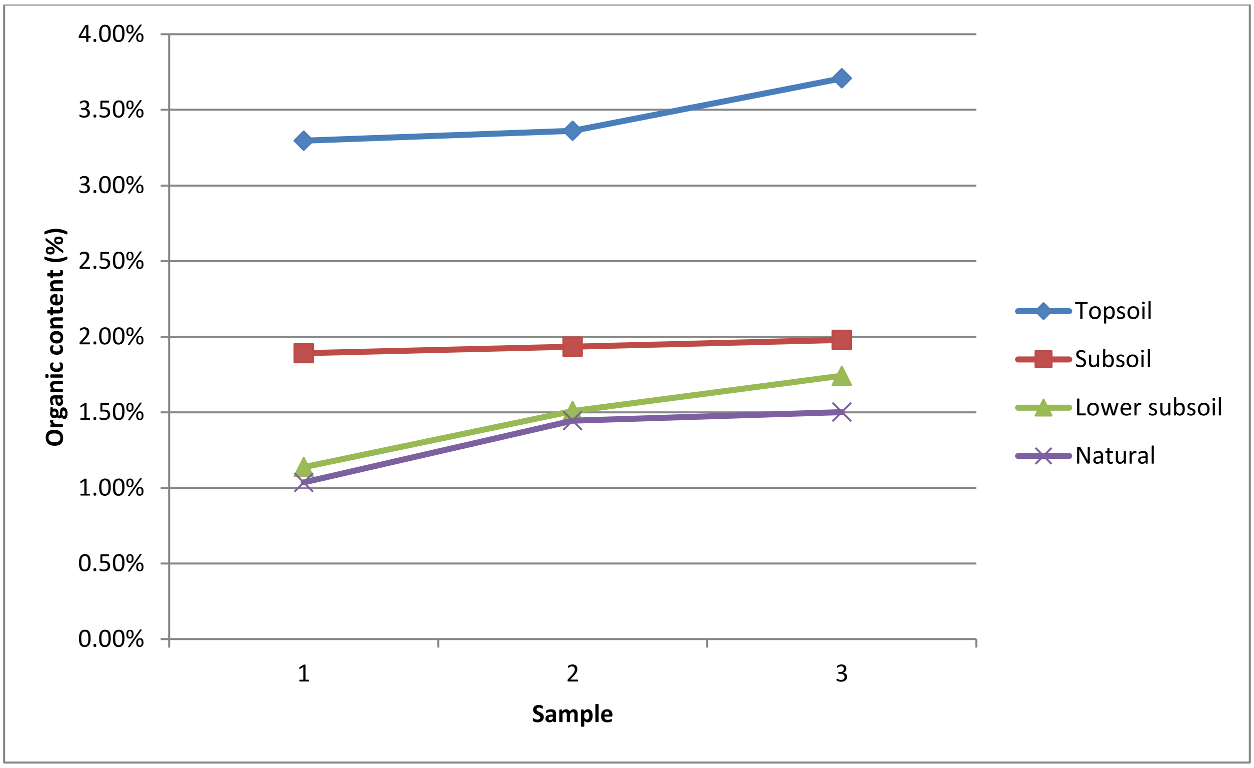


Figure 232: Organic content of soil samples from Wareham.

7.7.5 Texture results

All soil samples were assessed in the field for texture, all of which were identified as loamy sands. When samples were further analysed in the laboratory using the Malvern Mastersizer, 50% of the samples were verified as loamy sands, with 42% as sandy loams and 8% as sand. The texture of samples throughout the soil column varied little, as the close proximity of samples can be seen on the texture triangle (figure 233), with overall sand content of samples ranging from 71.51% to 87.24%.

The dominance of sand in the soil at Wareham will allow soil to drain well and rapidly, as was observed in the field during sampling. This will account for the very low water contents, lower organic contents and low conductivity levels recorded from samples taken. The small quantity of clay in samples, which range from 8.78% to 20.4%, will result in a small colloid fraction and low cation exchange capacity in the soil, allowing water and solutes to leach through the soil rapidly.

The high sand content will also encourage abrasion between lead bullets and soil particles. As discussed in section 2.1, researchers have disagreed as to whether clays or sands are more damaging to buried archaeological materials, though most agree that sand is more damaging. In the case of Wareham, it is evident that the sand texture has caused abrasive damage to the buried lead bullets and worn down their patinas.

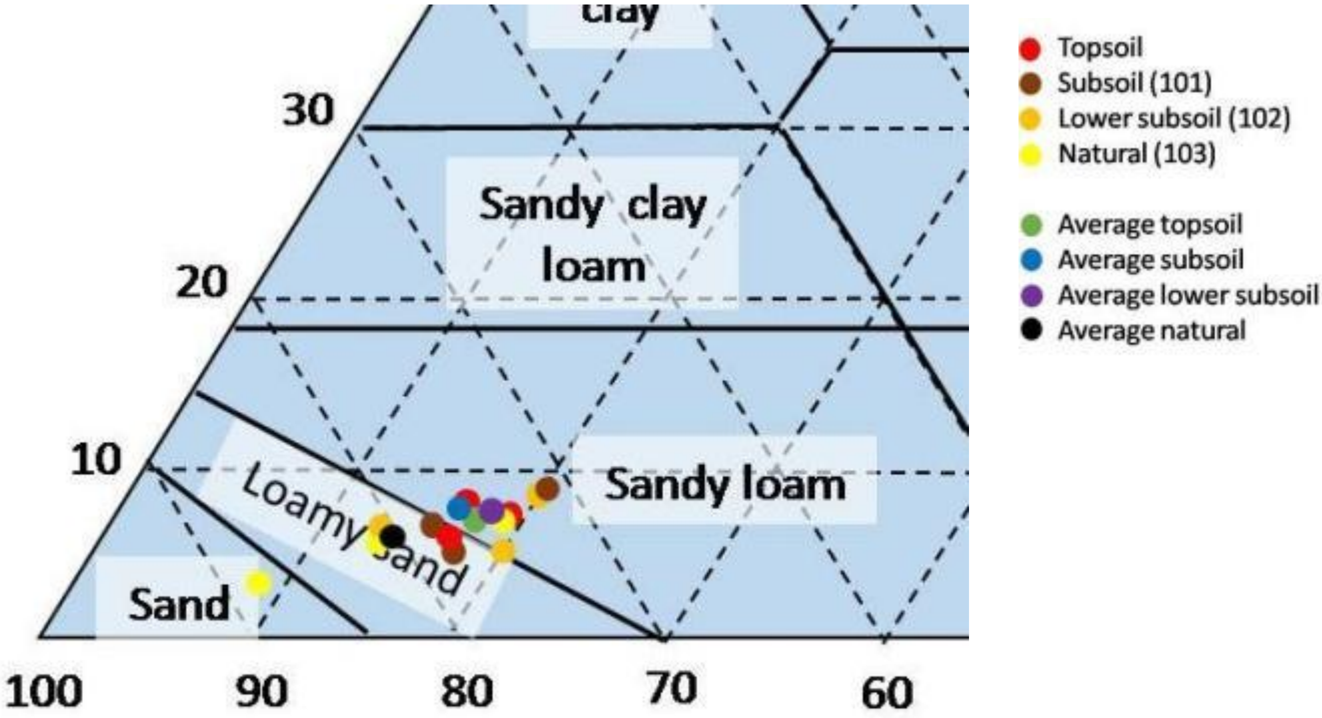


Figure 233: Texture triangle for all samples from Wareham by soil layer, highlighting small variation in texture classes.

7.7.6 Nitrate content results

Nitrate levels were recorded for all samples at Wareham and varied quite considerably. Topsoil levels were by far the highest recorded, averaging at 96.92±34.56mg/kg. These levels dropped dramatically in lower deposits. In subsoils the average content was 12.46±6.35mg/kg, lower subsoils 9.18±4.35mg/kg, and natural deposits averaged at 6.26±1.41mg/kg (figure 234). This drop in content at depths greater than 0.50m indicates a dramatic loss of nitrates from the soil and a lack of ability for the sandy soil to keep hold of ions as nitrate ions do not adhere to soil particles. The higher level in the topsoil is likely to be down to nitrification or the decomposition of organic matter on the surface of the soil, as well as from the application of manure. The levels are however somewhat surprising as nitrate is usually deficient in acid soil at levels <5.5 pH as nitrification is significantly reduced under these conditions (U.S.D.A. 2014) The moderate level of nitrates in the topsoil do not denote aggressive levels and do not pose a significant threat to the preservation of lead.

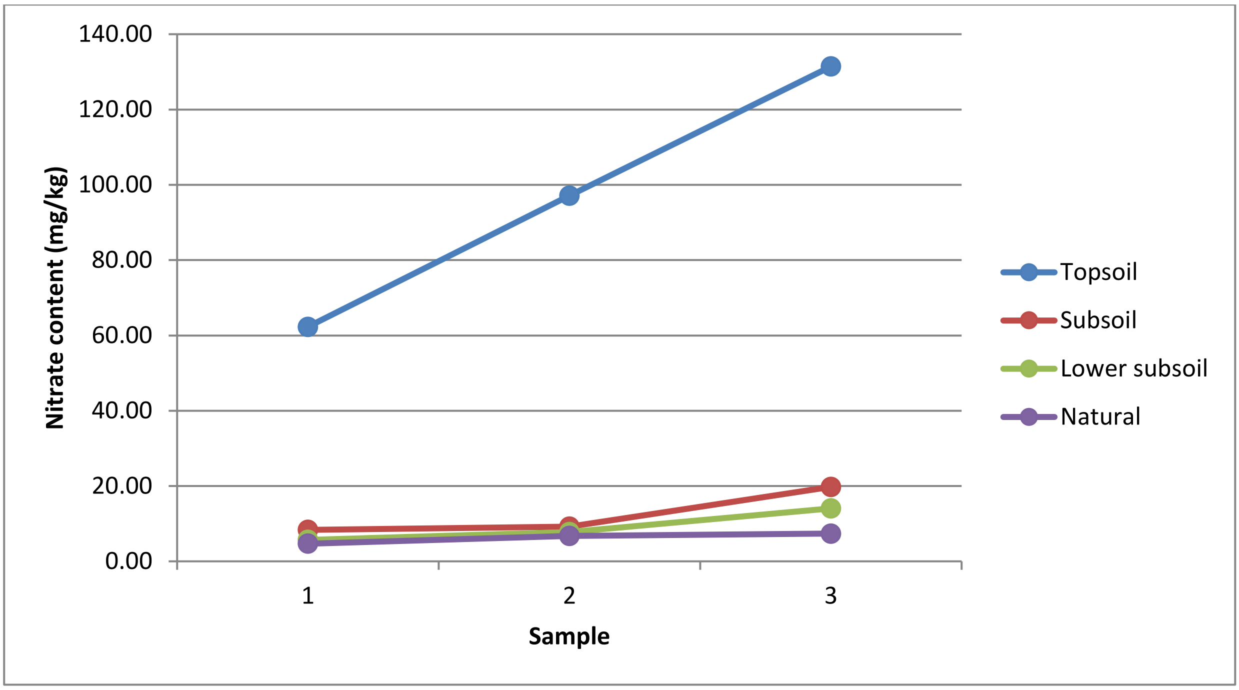


Figure 234: Nitrate concentration of soil layers across the site, indicating significantly higher levels in topsoil deposits.

7.7.7 Chloride content results

Chloride content in the soil column varied, but not as drastically as nitrate content. The highest recorded levels were in the lower subsoil, averaging at 153.10±87.64mg/kg. Topsoils average at 100.28±25.20mg/kg, subsoils at 103.60±40.93mg/kg, and natural deposits at 88.82±30.04mg/kg (figure 235). The UK soil observatory (UKSO) has recorded chloride levels around the site between 115.69-124.33mg/kg which is in the range of this project's recorded levels, though some samples were recorded significantly higher in the lower subsoil, up to 235mg/kg. This is much higher than average soil chloride concentrations of approximately 100mg/kg (Flowers 1988; Schulte 1999). There is potential for this to be an issue for the corrosion of metals in the soil as chloride ions are harmful, mobile, and as can be seen from the soil results are not easily leached out of the soil column, unlike nitrates which easily leach through the soil profile.

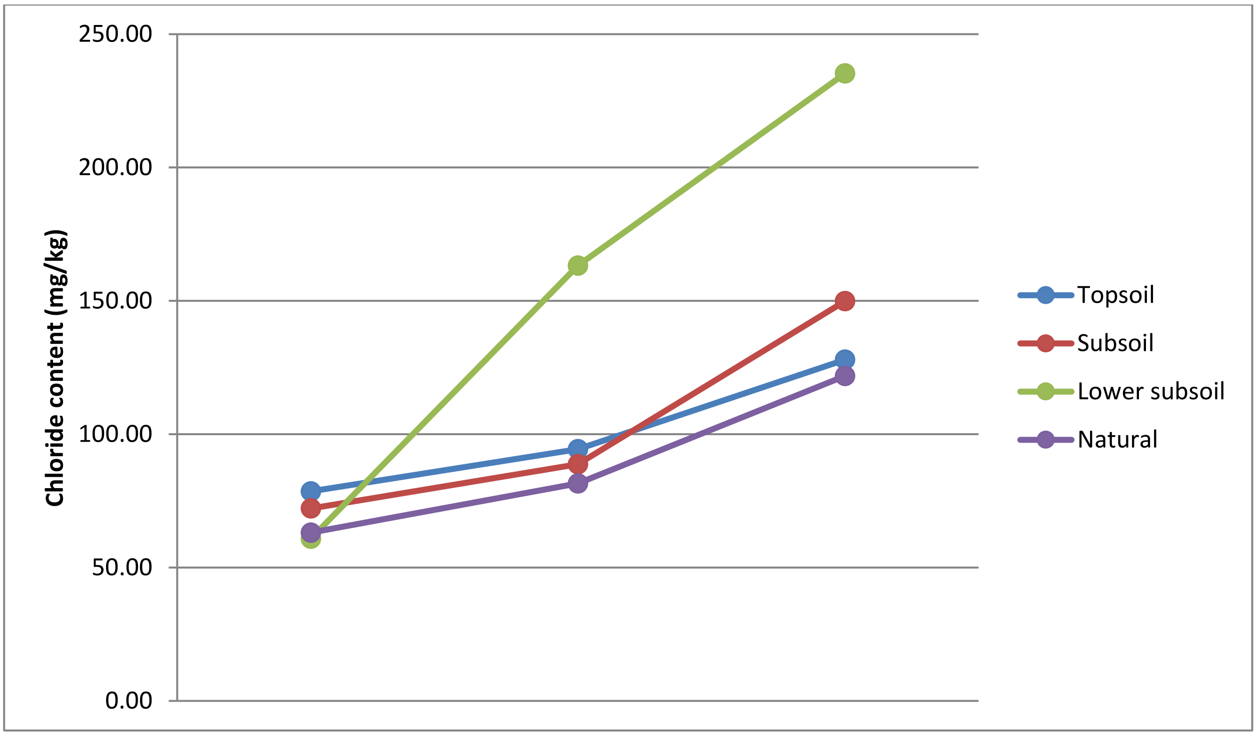


Figure 235: Chloride content of all soils sampled from Wareham.

7.8 Overview of the siege site of Wareham

When comparing the soil conditions at Wareham with the preservation of lead bullets, several attributes stand out:

-Low soil Ph

-Sandy textured soil

-Arable land use

-Level of corrosion and abraded surfaces

As the soil sampling was very restricted at Wareham, statistical analysis could not be carried out between the condition of the bullets and individual soil attributes. However, the two soil characteristics of pH and texture appear to be the dominant factors affecting the condition of bullets at the site. The acidity levels promote dissolution of patinas on bullets and the formation of soluble metal compounds that will diffuse away from the artefact rather than forming a solid passive protective layer over the surface of the bullet. This breakdown of surface layers will be accelerated further by the churning and compaction of the soil through ploughing which will encourage abrasion and stress corrosion cracks forming on the metal surface.

As these bullets have been under almost constant arable cultivation since at least the early 19th century, they have been subjected to an oxygenated, well drained environment where movement in the soil will encourage abrasion damage to bullets. Sandy particles are large and spherical and will cause abrasive damage when in contact with objects, unlike clay which comprises small smooth flat particles of <10µm (see section 2.3.3.2). 55% of the Wareham assemblage is abraded and this is no doubt due to the sandy texture of the soil being constantly ploughed and the bullets coming into contact with abrasive particles over decades of cultivation. It is important to note however, that for this collection some damage has been caused in the post excavation process due to poor storage of the material.

8 Comparison of data from Moreton Corbet, Edgehill and Wareham

A key aim in this research was to identify and address which factors have the most significant impact on the preservation or deterioration of lead in the ground. Three key parameters have been identified in previous work as affecting the overall trajectory of decay for buried metals:

-Soil chemistry and superficial geology

-Land use history (pasture or arable)

-Composition of objects

8.1 Soil chemistry and land use

Through the discussion of each case study above, particular soil attributes have been shown to have an influence on the condition of the lead bullets from each site. Statistical analysis did not provide many significant correlations on a site by site basis, which is likely to be due to the sample sizes. However, if all three sites are reviewed as a collective and each parameter compared to the condition of lead bullets from all three sites, much stronger relationships come to light. There appears to be a relationship between the condition of the bullets and the current land use on the sites which is also plotted for each parameter. In order to compare the relationship between the soil parameters and the condition of bullets from all three sites, the average condition of bullets from Wareham was used (12.4±2.3) in the analysis as the soil data was too restricted to make statistical justifications.

8.1.1 pH

When the pH of the soil and the condition of all bullets assessed from all three sites are compared, a fairly strong negative correlation is revealed (figure 236). This correlation is supported by the coefficient value of -0.781 which is statistically significant (table 74). This shows that there is a strong trend across the three sites that as pH increases, condition score declines and therefore the condition of bullets improves. The graph also makes apparent the range of pH and conditions from each case study. Edgehill's data lies predominantly at the alkaline end of the graph scoring relatively low condition scores meaning that the bullets are in good condition. Though Wareham is unfortunately only represented by a single averaged data point, it lies at the other extreme of acidity, and scores relatively high for overall bullet condition. Data from Moreton Corbet lies in between these two extremes, with a range of condition scores present in the slightly acidic to neutral soil conditions. This data represents the overall trend that as pH increases, so does the preservation of lead bullets. This data supports predictions that alkaline conditions promote the preservation of lead, whereas acidic conditions increase the chances of deterioration. If the data is plotted by land use type (figure 237), it is shown that the condition of bullets from pasture areas are noticeably and consistently better than the condition from arable areas, regardless of soil pH. However, no data has been collected from very acidic soils under permanent pasture and therefore it cannot be shown whether condition in pasture would deteriorate in very acidic conditions.

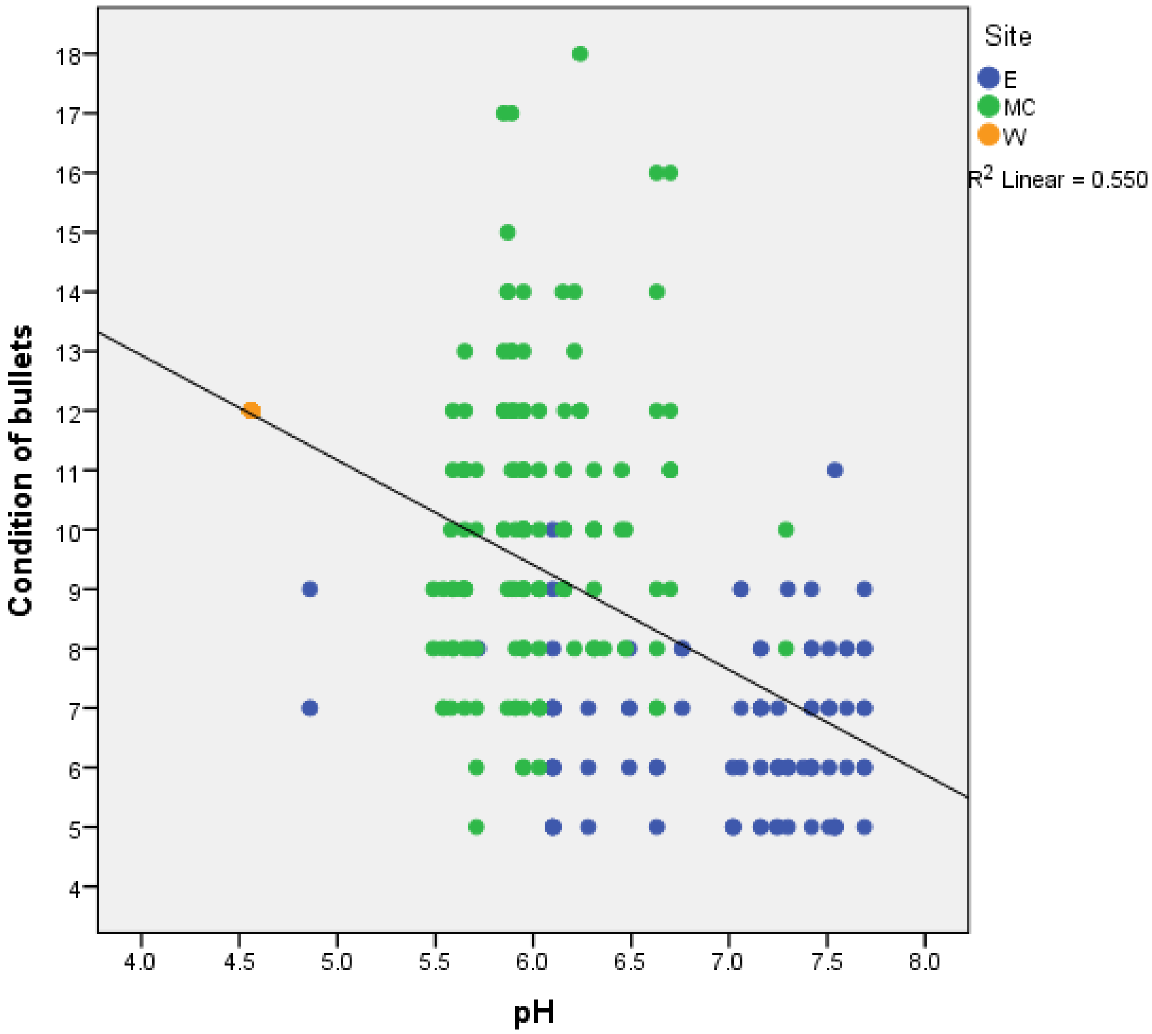


Figure 236: Scatter plot showing pH of soil against the condition of bullets from all three sites, showing a fairly strong negative correlation. E= Edgehill, MC= Moreton Corbet, W= Wareham. (Note that the error bars for these points are too small to show on the graph).

			pH	Condition
Spearman's rho	pH	Correlation Coefficient	1.000	-.781**
		Sig. (2-tailed)	.	.000
		N	518	518
	Condition	Correlation Coefficient	-.781**	1.000
		Sig. (2-tailed)	.000	.
		N	518	518

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

Table 74: Spearman's rank correlation coefficient of -0.781 for pH against condition of bullets which is statistically significant.

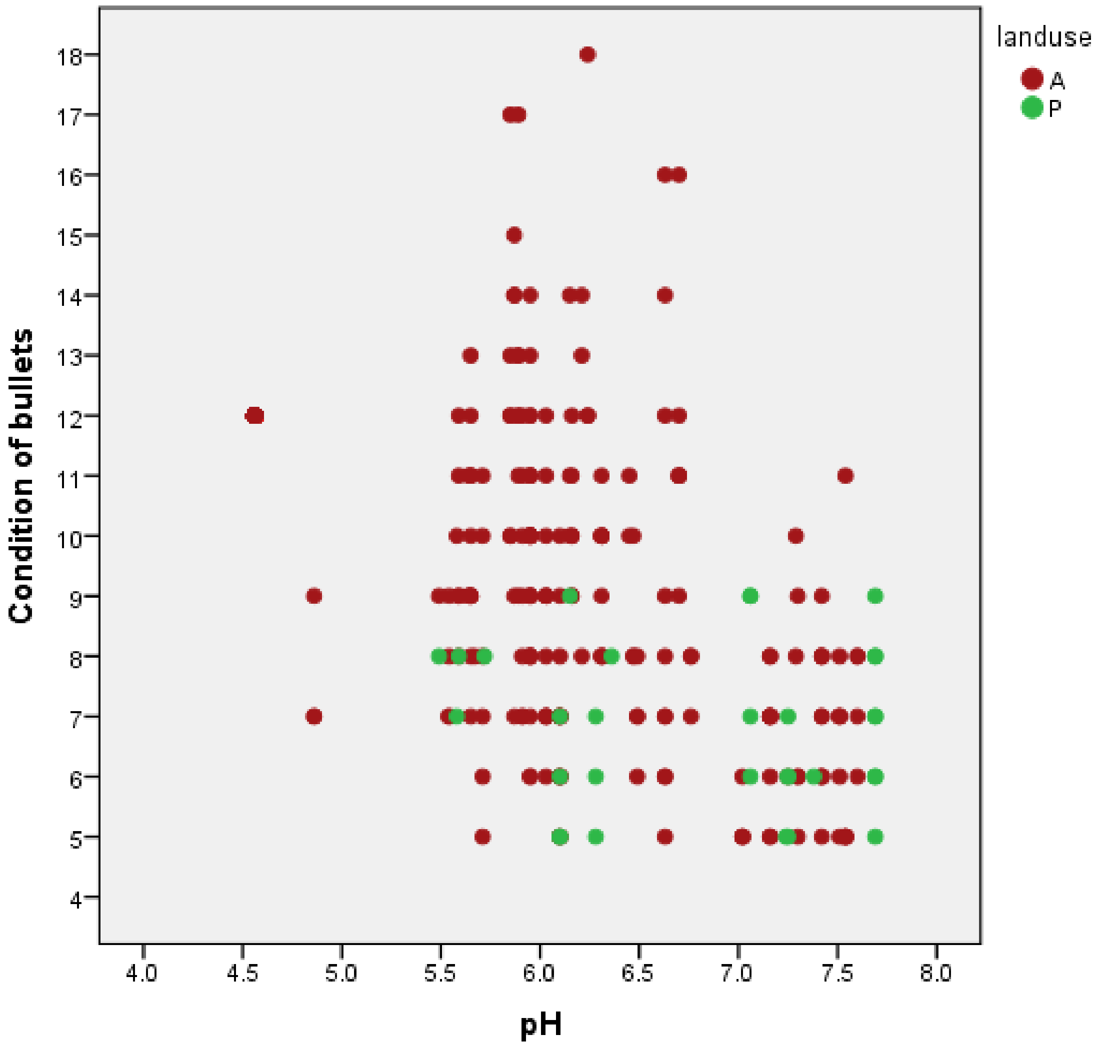


Figure 237: Scatter plot showing the pH of soil against the condition of bullets, displayed by land use type. A= current arable, P= current pasture.

8.1.2 Conductivity

When the conductivity of soil is compared to the condition of bullets from all three sites, a negative correlation is present (figure 238). There is a trend for condition to improve as conductivity increases, which does not support the prediction laid out in section 2.3.3.8 as increasing conductivity should in theory lead to increasing rates of corrosion. This negative correlation has a coefficient value of -0.690 and is statistically significant (table 75). Highest conductivity levels were recorded at Edgehill, even though this site has the best preservation, though conductivity at Edgehill ranges from low to moderately high. Lowest levels were recorded at Wareham which exhibits the worst preservation. It was shown that at Wareham conductivity has little impact on preservation due to lack of water retention in the soil. When the data is plotted by land use type it is evident that almost all bullets in pasture exhibit good condition scores and low levels of conductivity (figure 239). If the correlation coefficient is recorded for just pasture areas, the coefficient value becomes a slight positive correlation value of 0.434 (table 76).

This indicates that when dealing with pasture areas, increasing conductivity causes a decline in bullet preservation as condition score increases, which supports the theory laid out in section 2.3.3.8. However, the correlation remains strongly negative when just analysing bullets from arable fields which results in a correlation coefficient of -0.712 (table 77). This suggests that increasing conductivity in pasture fields has a damaging impact on bullets. However, increasing conductivity does not have as strong an impact on the deterioration of bullets in arable areas. More data would need to be collected from pasture areas in order to back up this theory, though it suggests that increasing levels of conductivity on pasture fields is more damaging than increasing conductivity levels on arable fields. This is important in terms of future management of archaeological sites. It appears important to avoid dramatically increasing conductivity levels in areas of long term pasture, by avoiding using chemical fertilisers and by refraining from converting pasture to arable cultivation.

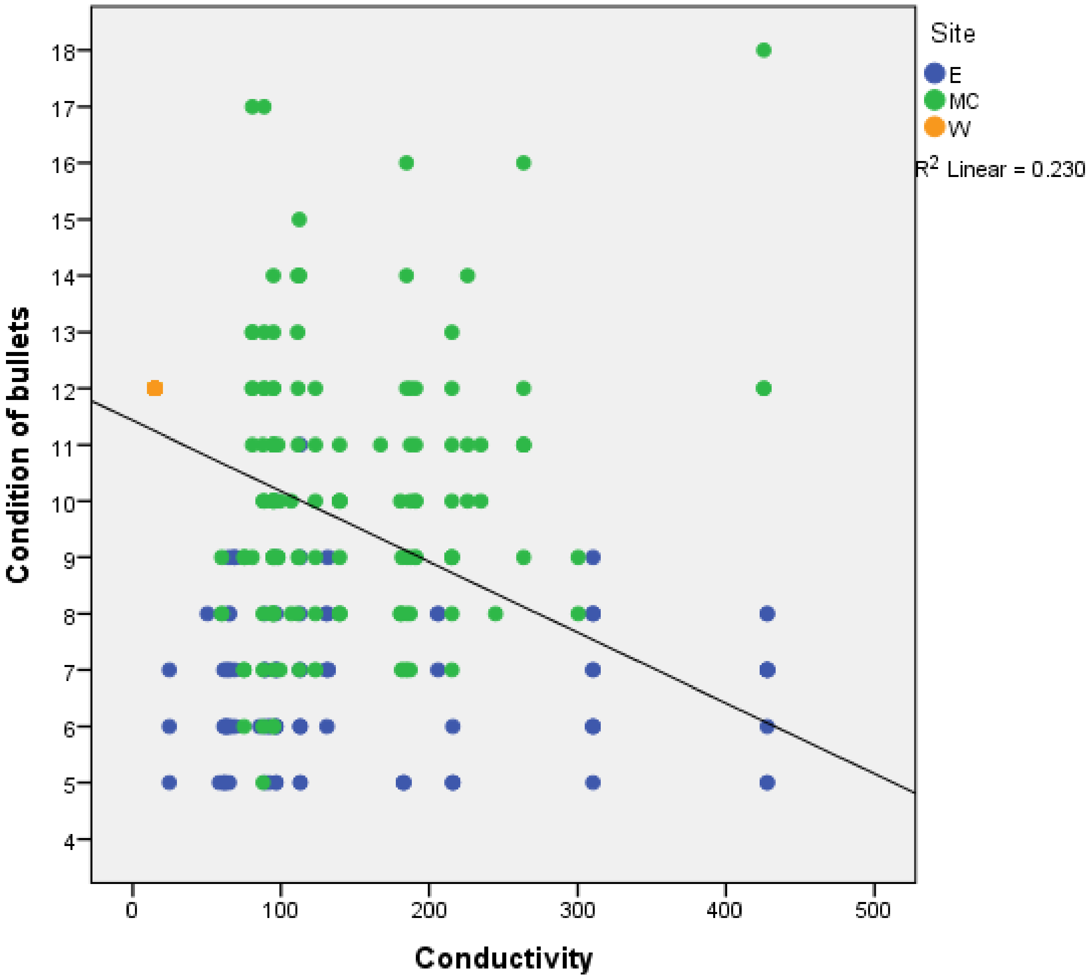


Figure 238: Scatter plot showing the conductivity of soil against the condition of bullets from all three sites, showing a negative correlation.

			Condition	Conductivity
Spearman's rho	Condition	Correlation Coefficient	1.000	-.690**
		Sig. (2-tailed)	.	.000
		N	518	518
	Conductivity	Correlation Coefficient	-.690**	1.000
		Sig. (2-tailed)	.000	.
		N	518	518

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

Table 75: Spearman's rank correlation coefficient of -0.690 for conductivity of soil against the condition of bullets, showing a statistically significant negative trend.

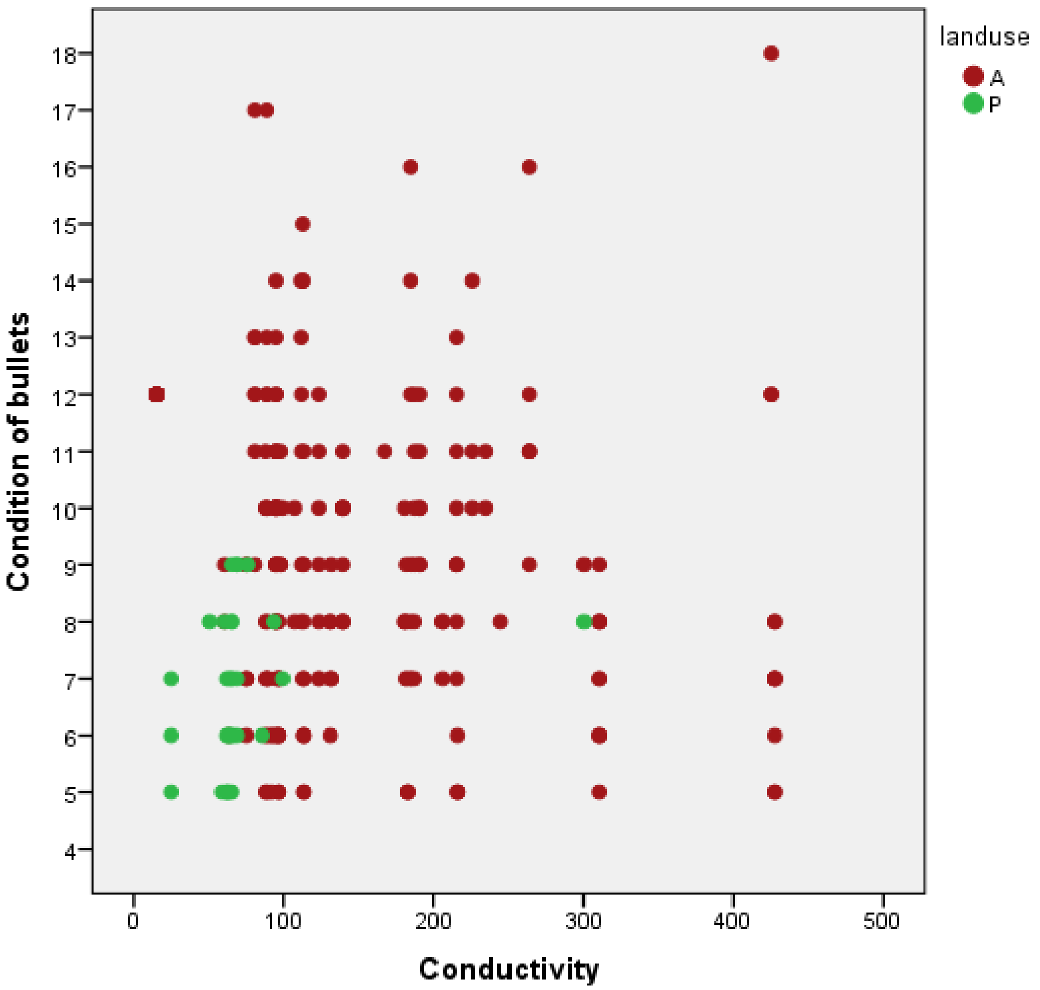


Figure 239: Scatter plot showing conductivity of soil against the condition of bullets, displayed by land use. Pasture areas show a positive correlation; as conductivity increases, so does condition score.

			Condition	Conduct
Spearman's rho	Condition	Correlation Coefficient	1.000	.434*
		Sig. (2-tailed)	.	.015
		N	31	31
	Conduct	Correlation Coefficient	.434*	1.000
		Sig. (2-tailed)	.015	.
		N	31	31

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

Table 76: Spearman's rank correlation coefficient of 0.434 for conductivity against the condition of bullets just in pasture fields.

			Conduct	Condition
Spearman's rho	Conduct	Correlation Coefficient	1.000	-.712**
		Sig. (2-tailed)	.	.000
		N	487	487
	Condition	Correlation Coefficient	-.712**	1.000
		Sig. (2-tailed)	.000	.
		N	487	487

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

Table 77: Spearman's rank correlation coefficient of -0.712 for conductivity against condition of bullets just in arable fields.

8.1.3 Water content

The relationship between the water content of soil and the condition of bullets results in a negative correlation; as water content increases, condition score drops and subsequently condition of bullets improves (figure 240). This does not support the prediction in section 2.3.8 as higher water contents should increase corrosion rates of lead. The correlation has a coefficient of -0.794 which is a fairly strong negative correlation and is statistically significant (table 78). The graph shows the difference between each site, with Edgehill exhibiting the highest water content levels with the best preservation. Moreton Corbet displays a great range of water contents and condition scores which suggests there is no clear trend between condition and water content at this site.

If the data is plotted by land use type, it is revealed that all pasture areas appear relatively high in water content, suggesting that higher water contents are not significantly affecting the condition of the lead objects (figure 241). Perhaps if the water contents measured were significantly higher than the range produced from these case studies, the trend may change. However, high water contents have the greatest impact on metal corrosion in the early stages of corrosion rather than later stages and may be less significant in their long term preservation (Angelini *et al.* 1998). Furthermore, it may be water fluctuations rather than water content which may have to most impact on preservation. It appears in this study that land use has a greater impact on the preservation of the bullets than the effect of soil water contents.

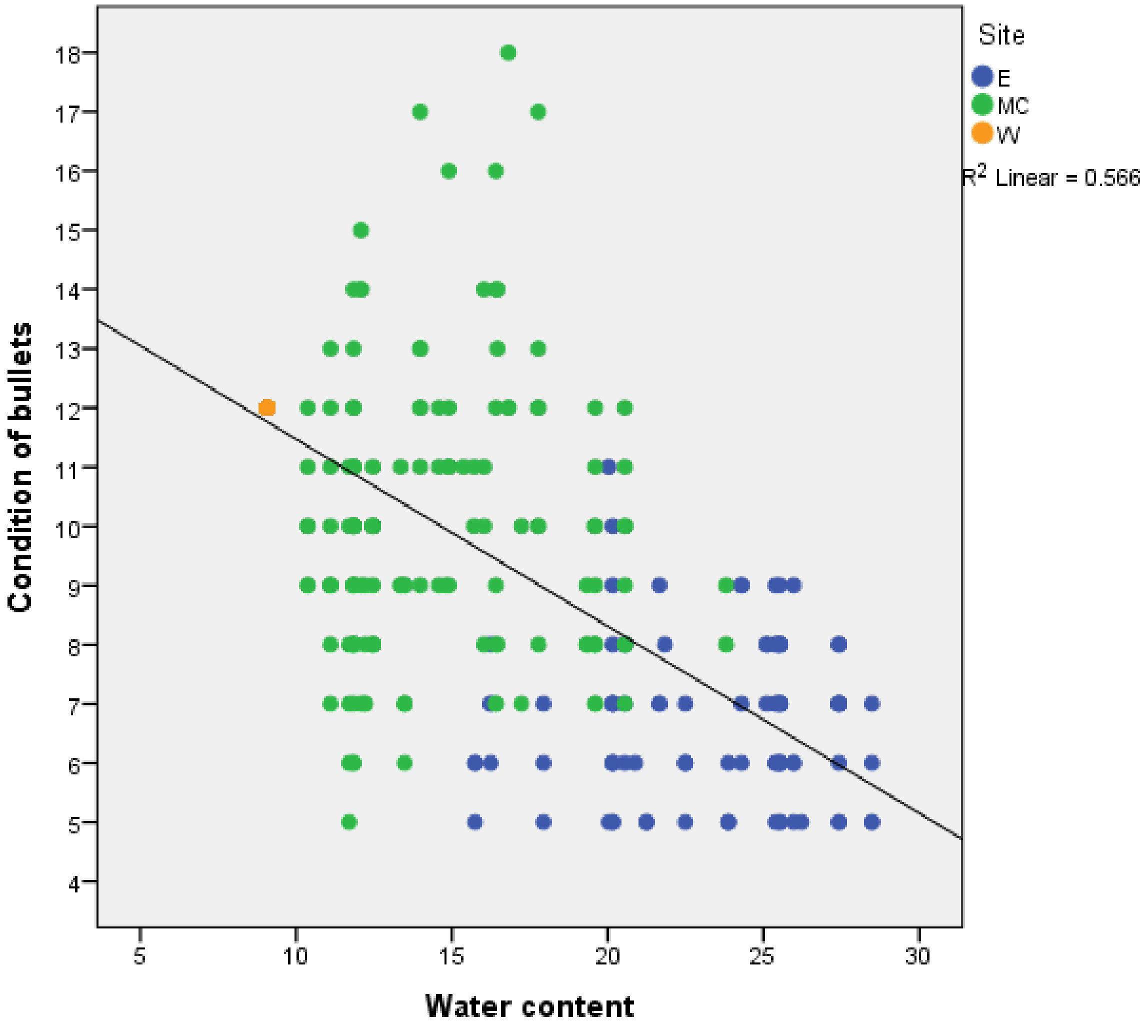


Figure 240: Scatter plot showing water content of soil against the condition of bullets, showing a significant negative correlation.

			Condition	Water
Spearman's rho	Condition	Correlation Coefficient	1.000	-.794**
		Sig. (2-tailed)	.	.000
		N	518	518
	Water	Correlation Coefficient	-.794**	1.000
		Sig. (2-tailed)	.000	.
		N	518	518

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

Table 78: Spearman's rank correlation coefficient of -0.794 for water content against condition of bullets, indicating a fairly strong negative correlation.

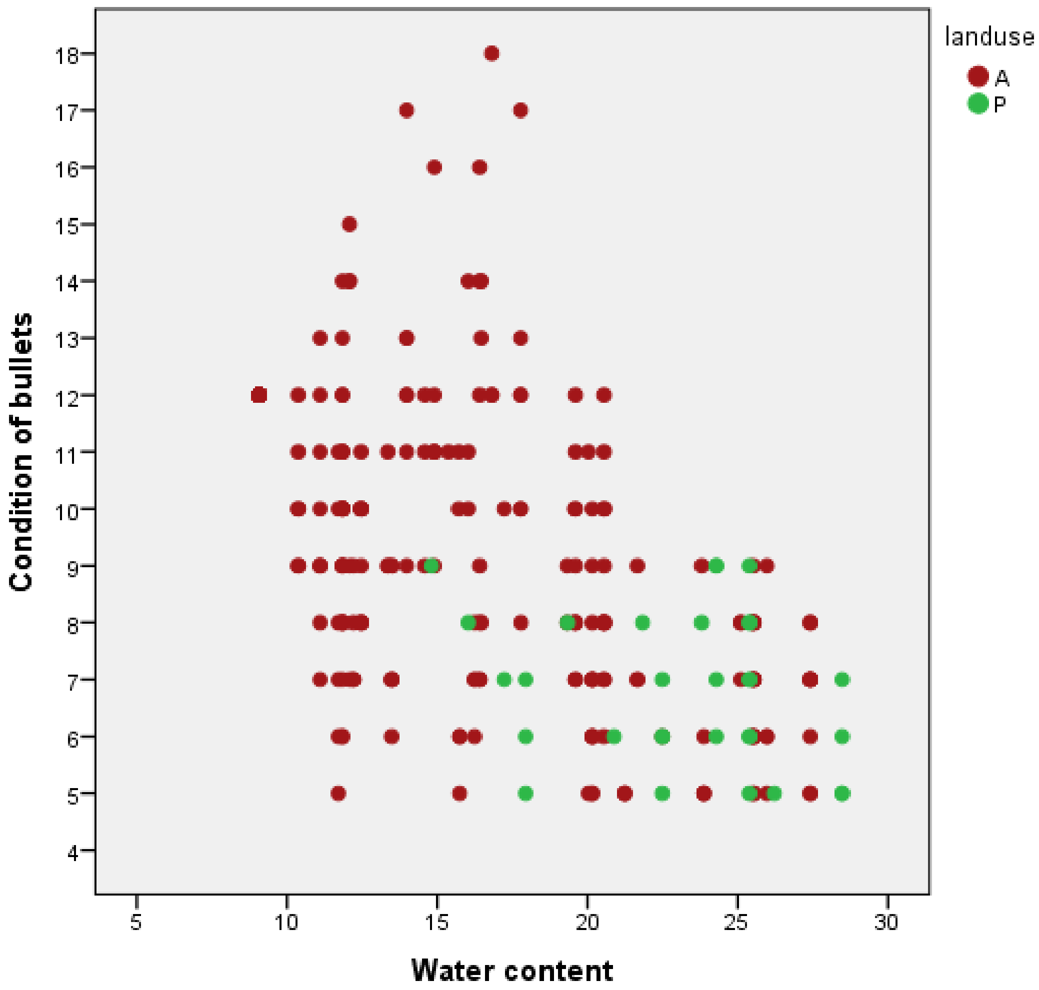


Figure 241: Scatter plot showing water content of soil against the condition of bullets, plotted by land use.

8.1.4 Organic content

When the condition of bullets is compared with the organic content of the soil, a relatively strong negative correlation is revealed, showing that as organic content increases, condition scores decrease (figure 242). This is the opposite of what would be predicted, as laid out in section 2.3.3.7. The correlation coefficient of -0.810 is strong and is statistically significant (table 79). It is revealed that Edgehill has higher organic content compared to the other two sites, though Edgehill bullets are in better condition, suggesting that organic content has not impacted their preservation. If the data is displayed by land use (figure 243), it is evident that pasture areas score low regardless of organic content, whereas in arable fields bullets can score high for condition even in areas of low organic content. Again, similar to the water content results, it appears that land use impacts more on the preservation of bullets than the soil organic content.

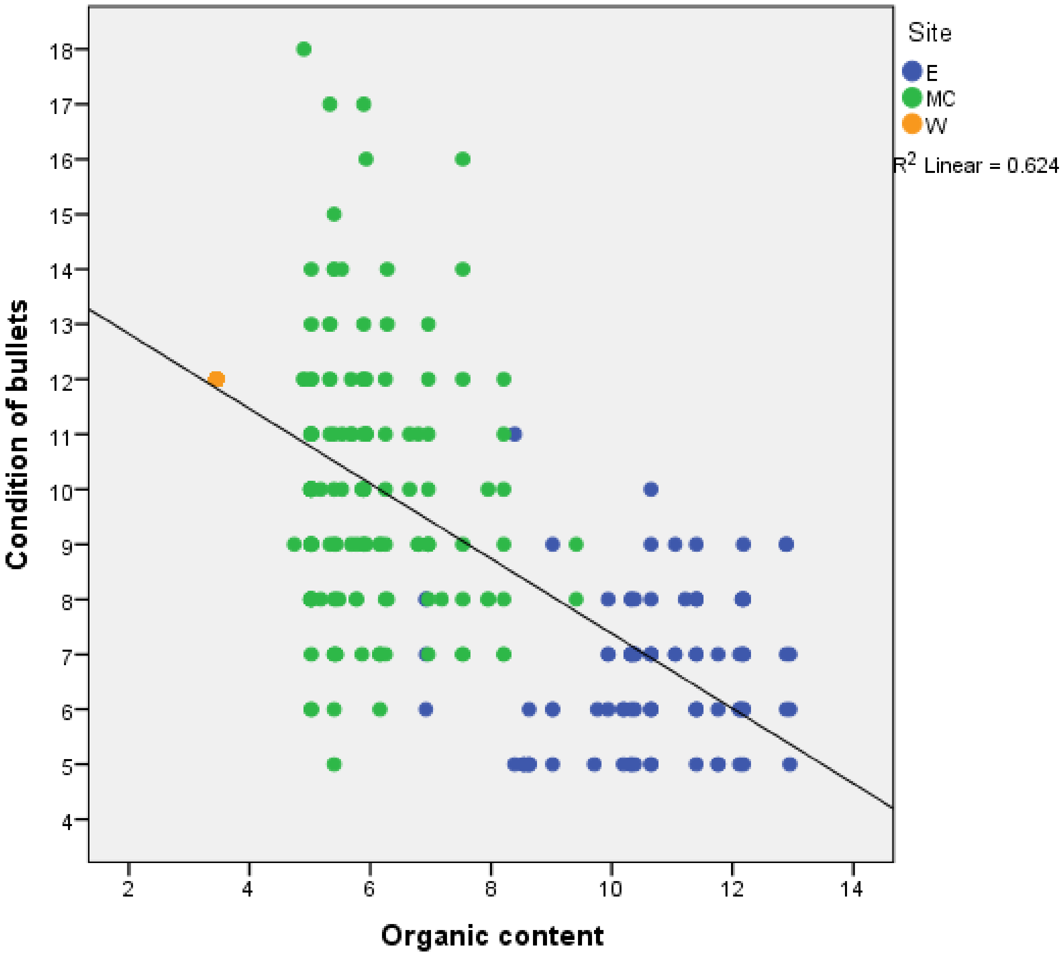


Figure 242: Scatter plot showing organic content of soil against the condition of bullets, revealing a strong negative correlation.

			Condition	Organic
Spearman's rho	Condition	Correlation Coefficient	1.000	-.810**
		Sig. (2-tailed)	.	.000
		N	518	518
	Organic	Correlation Coefficient	-.810**	1.000
		Sig. (2-tailed)	.000	.
		N	518	518

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

Table 79: Spearman's rank correlation coefficient of -0.810 for organic content against the condition of bullets showing a strong negative correlation.

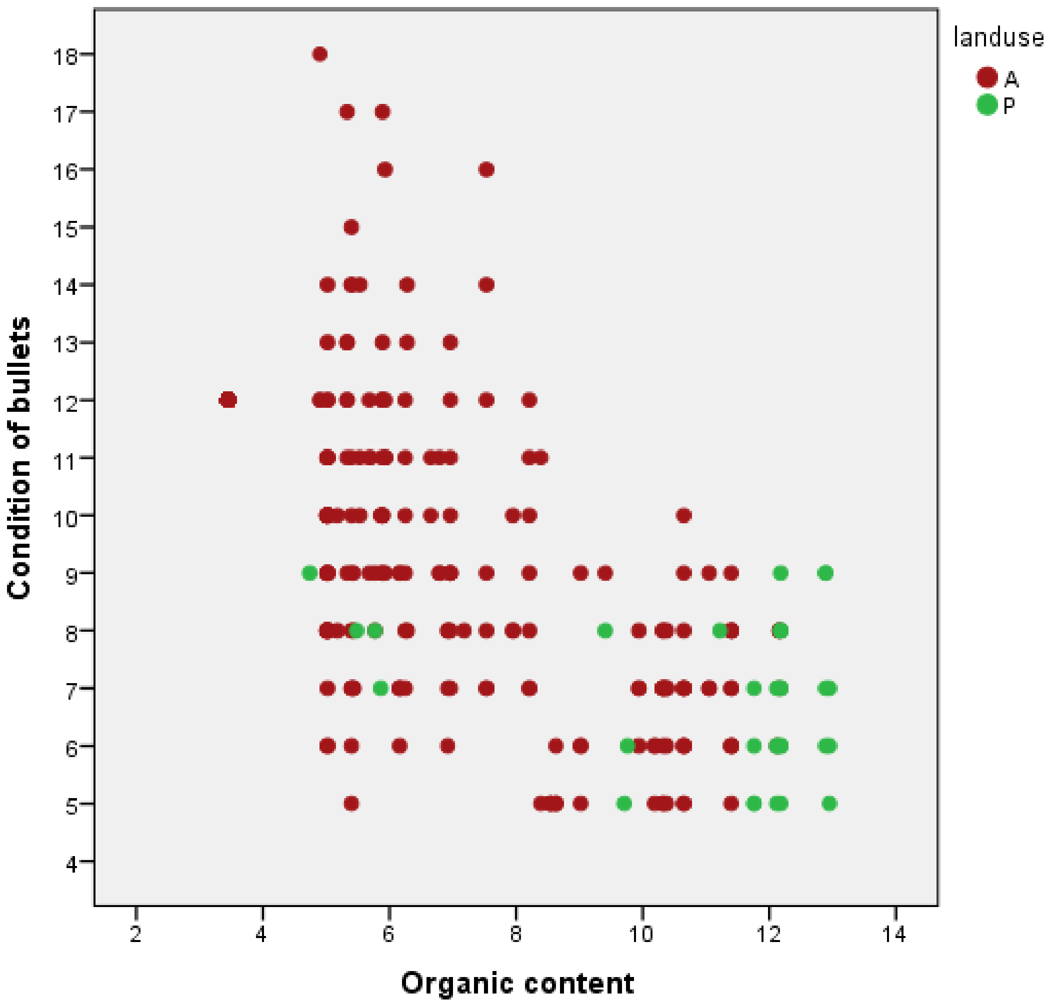


Figure 243: Scatter plot showing organic content of soil against the condition of bullets, plotted by land use.

8.1.5 Texture

The correlation between the clay content of the soil and the condition of bullets from all three sites is negative (figure 244). As the clay content increases, there is a trend for condition score to drop and therefore the condition of bullets to improve. This is supported by the coefficient value of -0.643 which is statistically significant (table 80). As discussed in section 2.1, there is debate as to whether clay promotes or impedes the preservation of metal in the soil. However, the general consensus is that clay will promote good preservation, as supported by the results in this study.

As a contrast, the relationship between sand content and the condition of bullets shows a slight positive correlation; that as sand content increases, condition score increases and therefore the condition of bullets worsens (figure 245). However. the coefficient is not as strong as for the clay content, with the coefficient value for sand at 0.264 which is significant, but does not represent a particularly strong correlation (table 81). This implies that clay content has a greater impact on preserving bullets than sand does on degrading bullets.

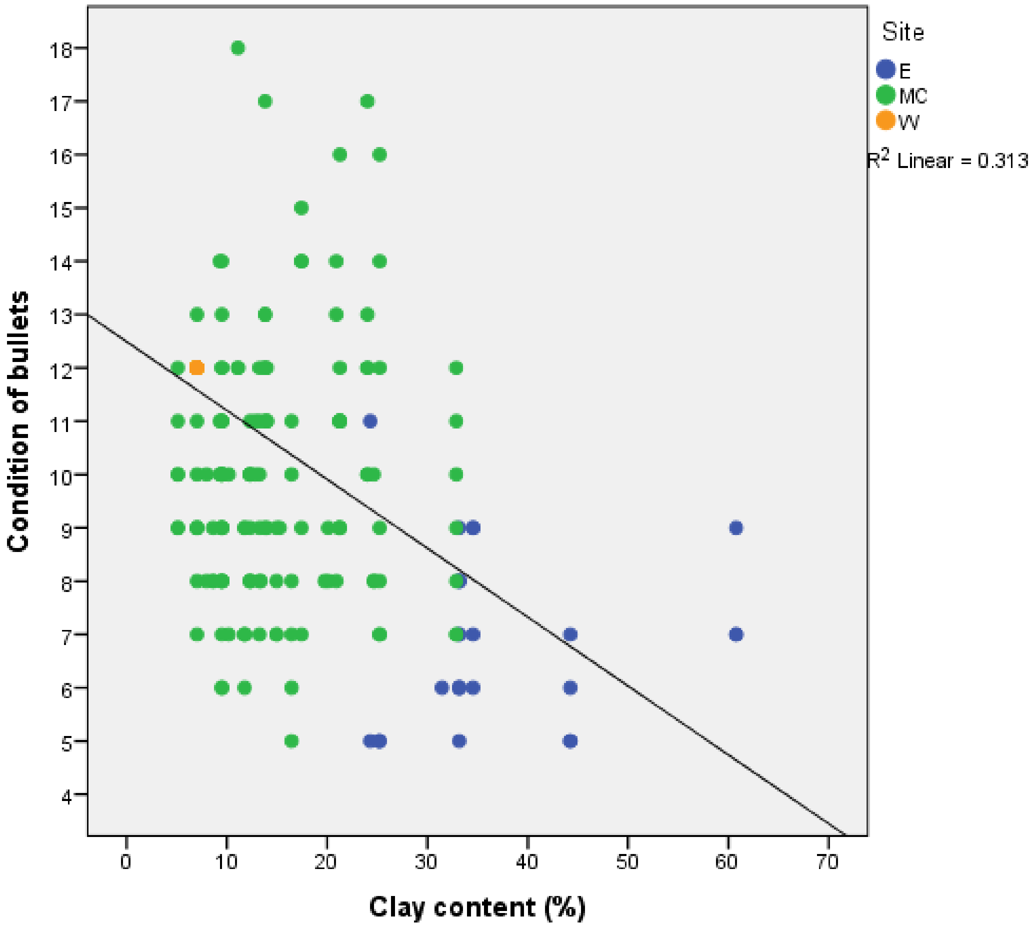


Figure 244: Scatter plot showing the clay content of the soil against the condition of bullets, indicating a negative correlation.

			Condition	Clay
Spearman's rho	Condition	Correlation Coefficient	1.000	-.643**
		Sig. (2-tailed)	.	.000
		N	518	450
	Clay	Correlation Coefficient	-.643**	1.000
		Sig. (2-tailed)	.000	.
		N	450	450

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

Table 80: Spearman's rank correlation coefficient of -0.643 for the clay content of soil against the condition of bullets.

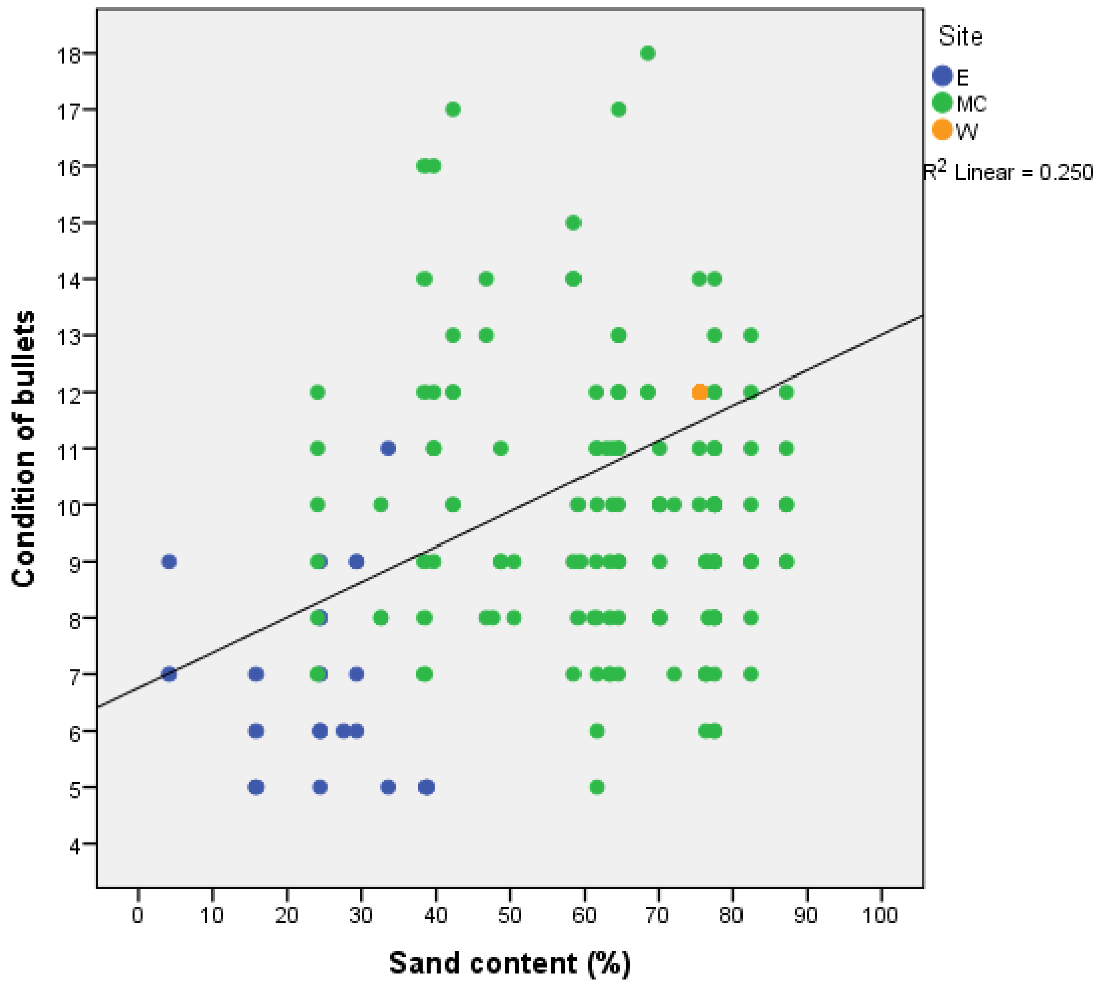


Figure 245: Scatter plot showing the sand content of soil against the condition of bullets, displaying a slight positive correlation.

			Condition	Sand
Spearman's rho	Condition	Correlation Coefficient	1.000	.264**
		Sig. (2-tailed)	.	.000
		N	518	450
	Sand	Correlation Coefficient	.264**	1.000
		Sig. (2-tailed)	.000	.
		N	450	450

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

Table 81: Spearman's rank correlation coefficient for the sand content of soil against the condition of bullets.

8.1.6 Nitrate content

A slight negative correlation occurs when the nitrate content of the soil is compared to the condition of bullets from all three sites (figure 246). The coefficient for this relationship is -0.492 and is statistically significant (table 82). However, looking at the graph the data appears relatively dispersed. The data is more insightful when displayed by land use type (figure 247). All the pasture areas display the lowest levels of nitrates and are better preserved in general. This suggests that, even though the data reveals a negative relationship, low nitrate levels in pasture and higher levels in arable have impacted on the preservation of lead bullets.

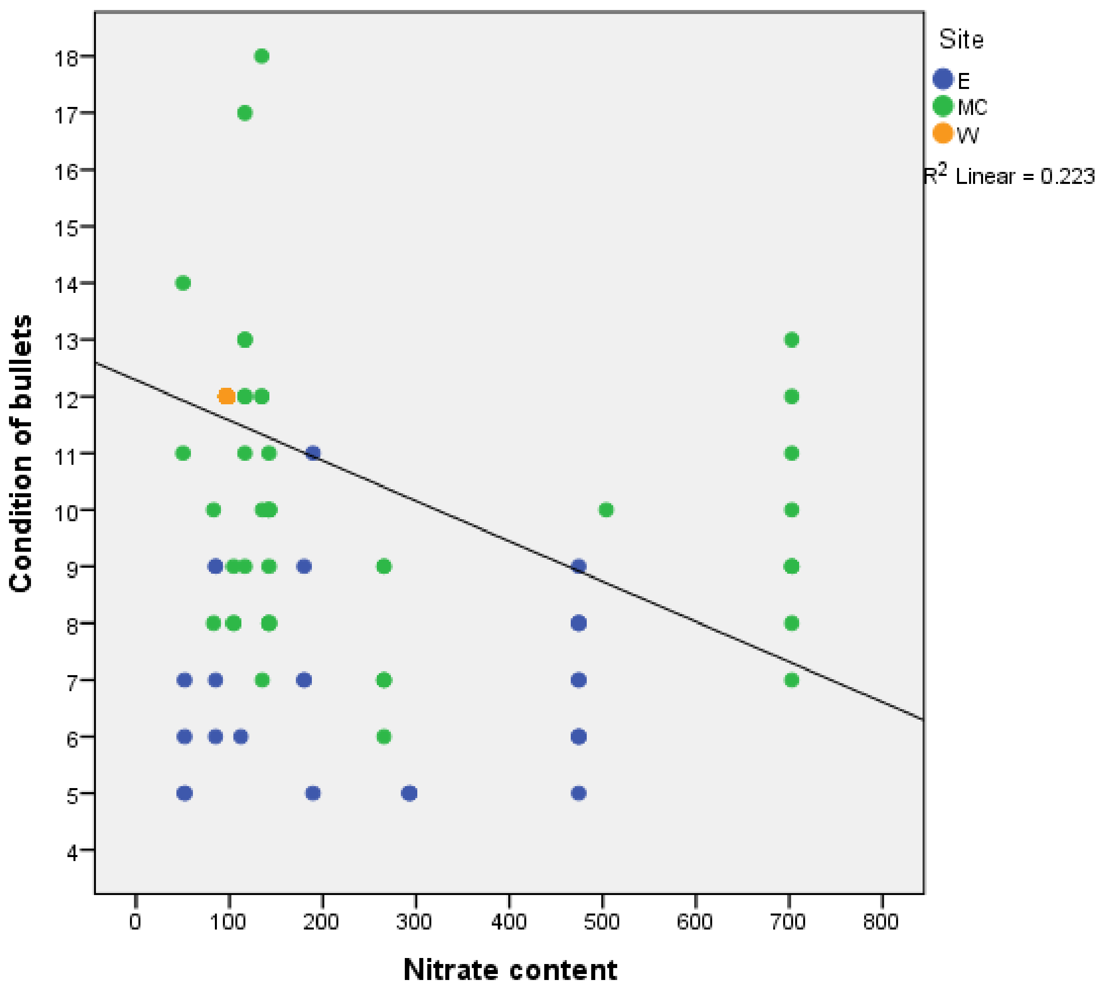


Figure 246: Scatter plot showing the nitrate content of soil against the condition of bullets.

			Condition	Nitrate
Spearman's rho	Condition	Correlation Coefficient	1.000	-.492**
		Sig. (2-tailed)	.	.000
		N	518	351
	Nitrate	Correlation Coefficient	-.492**	1.000
		Sig. (2-tailed)	.000	.
		N	351	351

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

Table 82: Spearman's rank correlation coefficient of -0.492 for the nitrate content of soil against the condition of bullets.

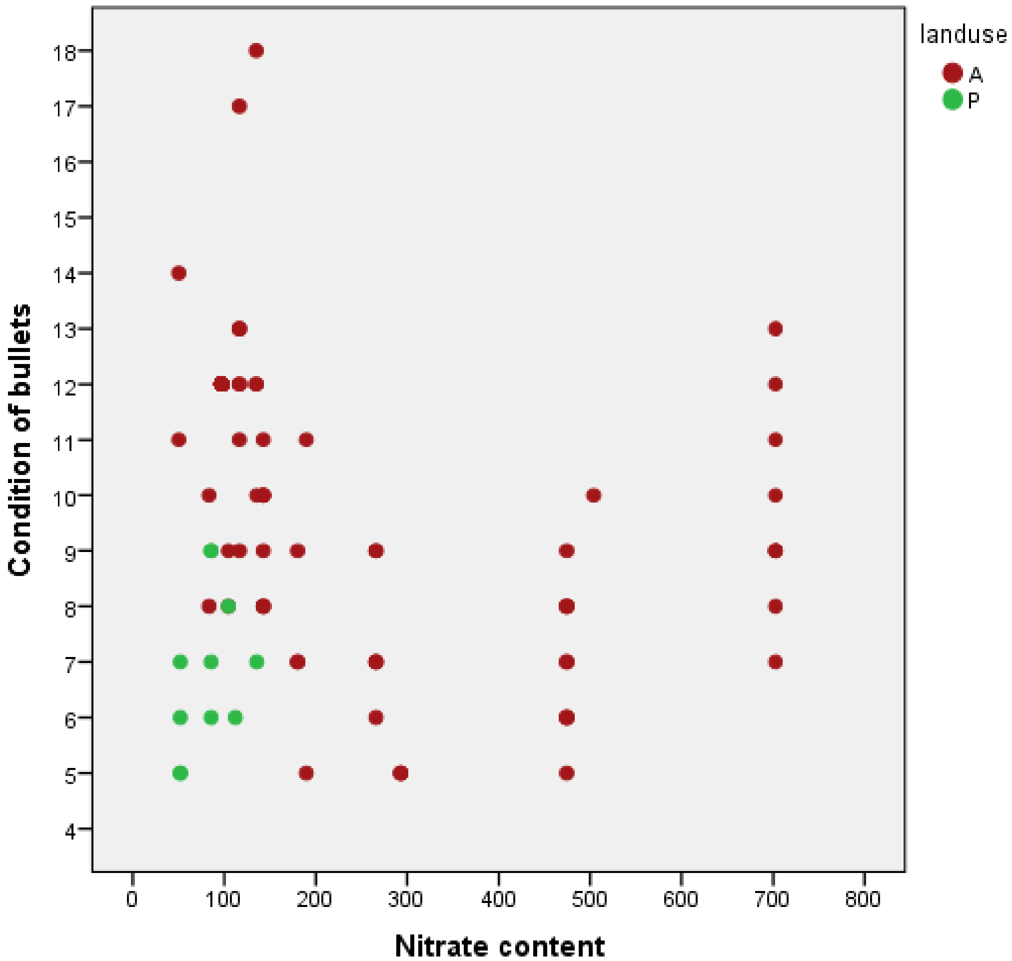


Figure 247: Scatter plot showing the nitrate content of soil against the condition of bullets, plotted by land use. Bullets in pasture consistently exhibit low levels of nitrates.

8.1.7 Chloride content

When the chloride content of the soil is compared the condition of bullets, a strong positive correlation is present, showing that condition scores increase with increasing chloride content (figure 248). This is what was predicted; that as the chloride levels in the soil increase, the condition of lead will worsen and therefore bullets will score higher. The correlation has a coefficient of 0.837 which is statistically significant (table 83). The strength of the coefficient indicates that chloride content may have a strong impact on the condition of lead in the ground. It appears that the land use is less significant when assessing chloride content, as pasture fields still record moderate levels of chlorides, suggesting that levels higher than 75mg/kg are required to increase the damage to bullets (figure 249). However, the samples tested for chloride content were limited and more data would be needed to be collected over an annual basis for stronger conclusions.

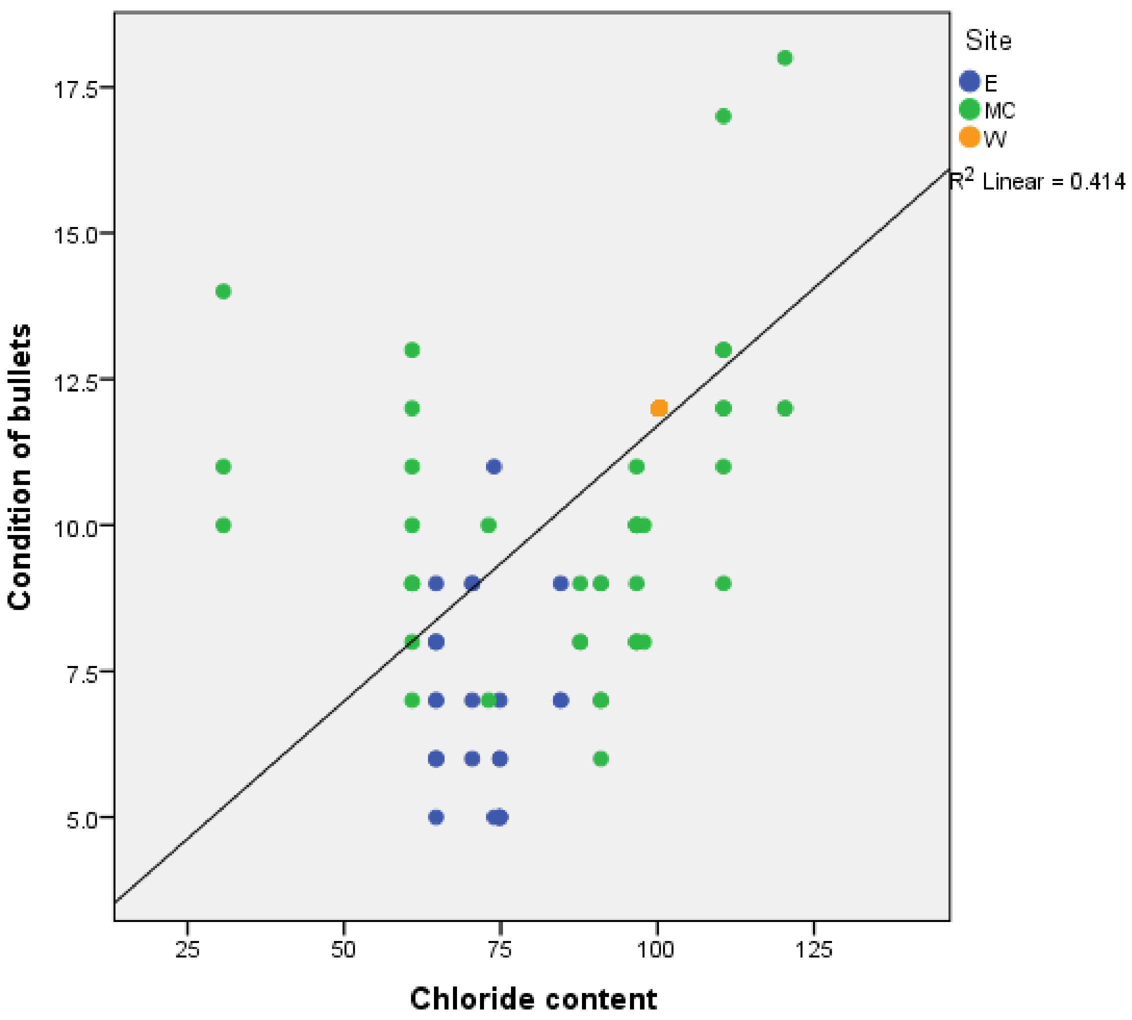


Figure 248: Scatter plot showing the chloride content of soil against the condition of bullets, showing a slightly positive correlation.

			Condition	Chloride
Spearman's rho	Condition	Correlation Coefficient	1.000	.837**
		Sig. (2-tailed)	.	.000
		N	518	351
	Chloride	Correlation Coefficient	.837**	1.000
		Sig. (2-tailed)	.000	.
		N	351	351

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

Table 83: Spearman's rank correlation coefficient of 0.837 for the chloride content of soil against the condition of bullets, significant at the 0.01 level.

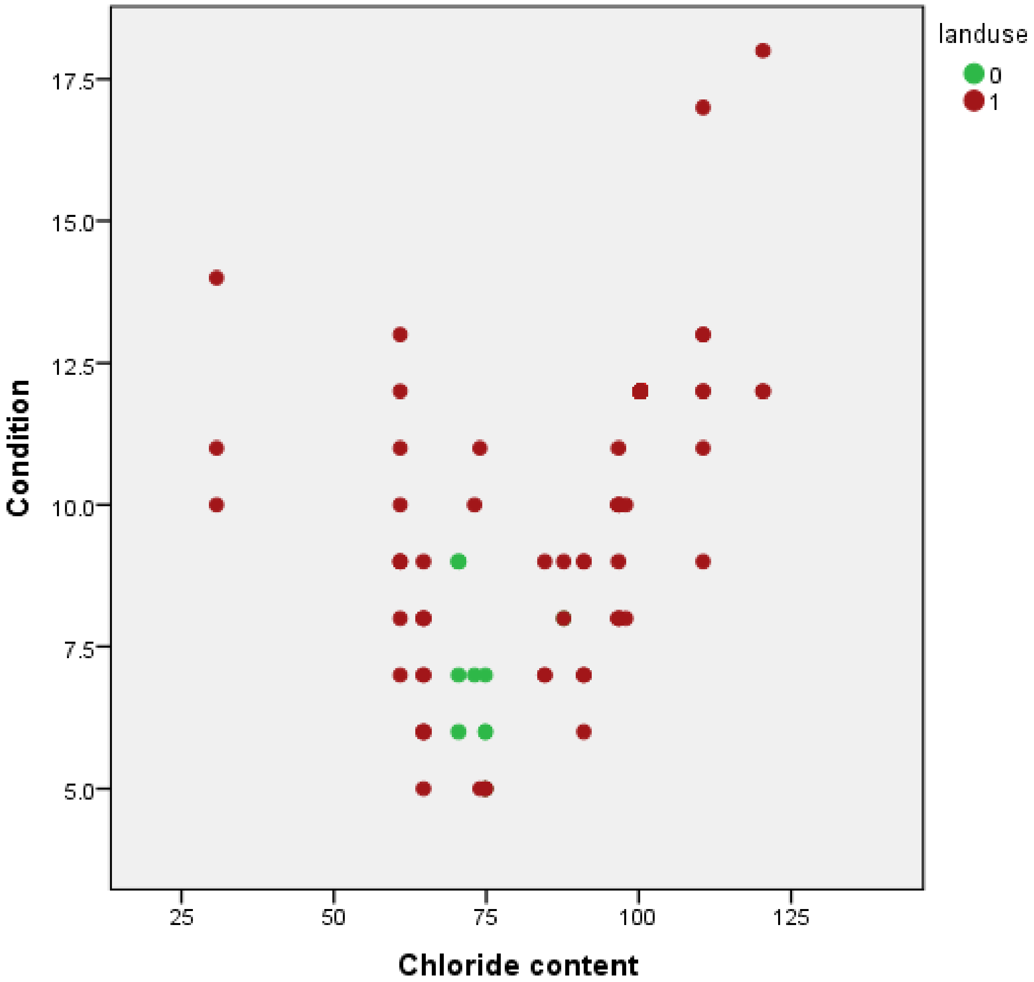


Figure 249: Scatter plot showing the chloride content of soil against the condition of bullets, plotted by land use. Green= arable, red= pasture.

8.2 Abrasion

A pattern which emerged through the case study analyses was whether assemblages contained bullets with abrasion damage. The impact of clay and sand on the preservation or degradation of lead is also supported by abrasion data. If the clay content of the soil is compared to the number of bullets abraded and those not abraded, a slight negative correlation is present; as clay content increases, there is a slight tendency for bullets to not be abraded. This correlation has a coefficient value of -0.200 which is statistically significant (table 84). There is a similarly positive correlation when the sand content of the soil is compared to the number of abraded bullets; as sand content increases, there is a slight trend for more bullets to be abraded. However, though this relationship is statistically significant, the correlation is weak as the value is only 0.097 (table 85). This indicates that clay content tends to reduce the number of abraded bullets (figure 250).

From the case study analyses it would be expected for this relationship to be more significant; Edgehill, which is predominantly clay, revealed 9% of the assemblage to be abraded, whilst Wareham, which is predominantly sand, exhibited a 55% abrasion rate. Perhaps it is not just the texture that affects the abrasion on bullets, but the period under cultivation. Wareham has been under cultivation since at least the mid 19th century, whereas Edgehill has only been ploughed regularly in the last few decades and may account for the low percentage of abraded bullets. If the relationship between the number of abraded bullets and current land use is plotted, there is a correlation coefficient value of 0.193, indicating that bullets are more prone to developing abrasion damage under arable cultivation (table 86). Soil texture as well as land use play a significant role in the abrasion and deterioration of bullets and it appears that clay soils reduce abrasion rates, therefore preserving surface details on bullets better, whilst sandy soils increase the rate of abrasion and leave bullets more vulnerable to surface detail loss. This could be significant when designing strategies to reduce the decay of buried assemblages on agricultural land. It appears that reducing ploughing on sandy soils is an important step to consider.

			Abrasion	Clay
Spearman's rho	Abrasion	Correlation Coefficient	1.000	-.200**
		Sig. (2-tailed)	.	.000
		N	518	450
	Clay	Correlation Coefficient	-.200**	1.000
		Sig. (2-tailed)	.000	.
		N	450	450

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

Table 84: Spearman’s rank correlation coefficient for the clay content of soil against the number of abraded bullets, showing a slight tendency for bullets to be abraded less with increasing clay content.

			Abrasion	Sand
Spearman's rho	Abrasion	Correlation Coefficient	1.000	.097*
		Sig. (2-tailed)	.	.040
		N	518	450
	Sand	Correlation Coefficient	.097*	1.000
		Sig. (2-tailed)	.040	.
		N	450	450

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

Table 85: Spearman’s rank correlation coefficient for the sand content of soil against abraded bullets, showing a very slight tendency for bullets to be abraded more with increasing sand content.

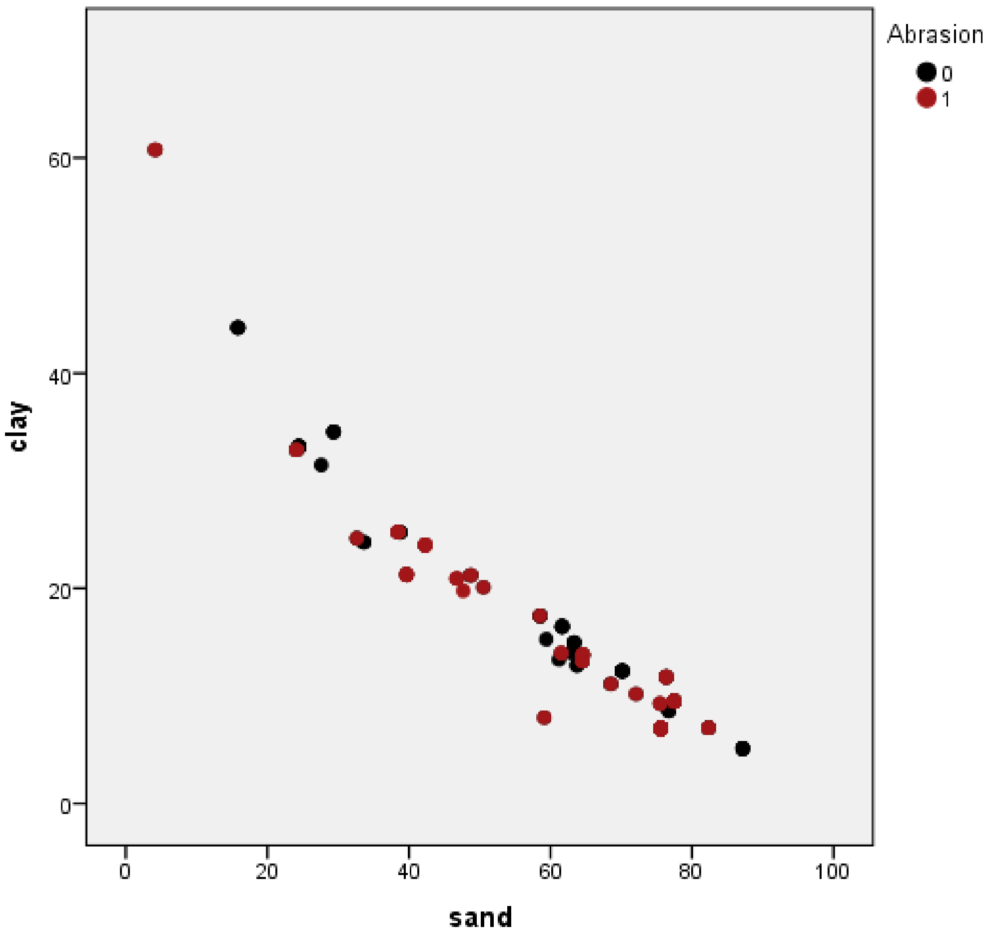


Figure 250: Scatter plot displaying sand content against clay content of soil and corresponding abraded and non-abraded bullets. black= not abraded, red= abraded.

			Abrasion	Land use
Spearman's rho	Abrasion	Correlation Coefficient	1.000	.193**
		Sig. (2-tailed)	.	.000
		N	518	518
	Land use	Correlation Coefficient	.193**	1.000
		Sig. (2-tailed)	.000	.
		N	518	518

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

Table 86: Spearman's rank correlation coefficient for abrasion of bullets against land use. A coefficient of 0.193 indicates a slight tendency for bullets to be more abraded in arable areas.

8.3 Metallic composition

8.3.1 Results

One of the aims of this research is to establish whether the metallic composition of the lead bullets have had an impact on their preservation. 79 lead bullets were analysed using pXRF for this study; 28 from Wareham, 30 from Moreton Corbet, and 21 from Edgehill. The average lead content of the analysed bullets was 91.75±7.55%. 89.87% of the bullets (71 in total) had over 90% lead content, with only eight bullets having a composition lower than 90% lead (figure 251).

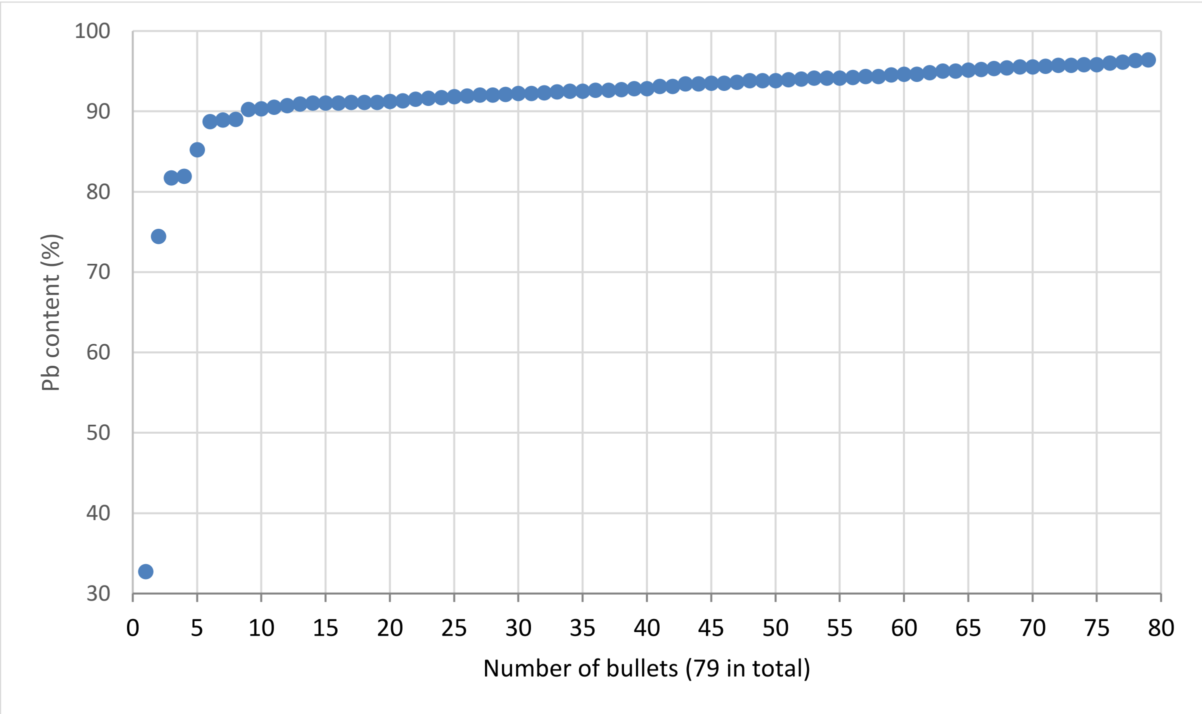
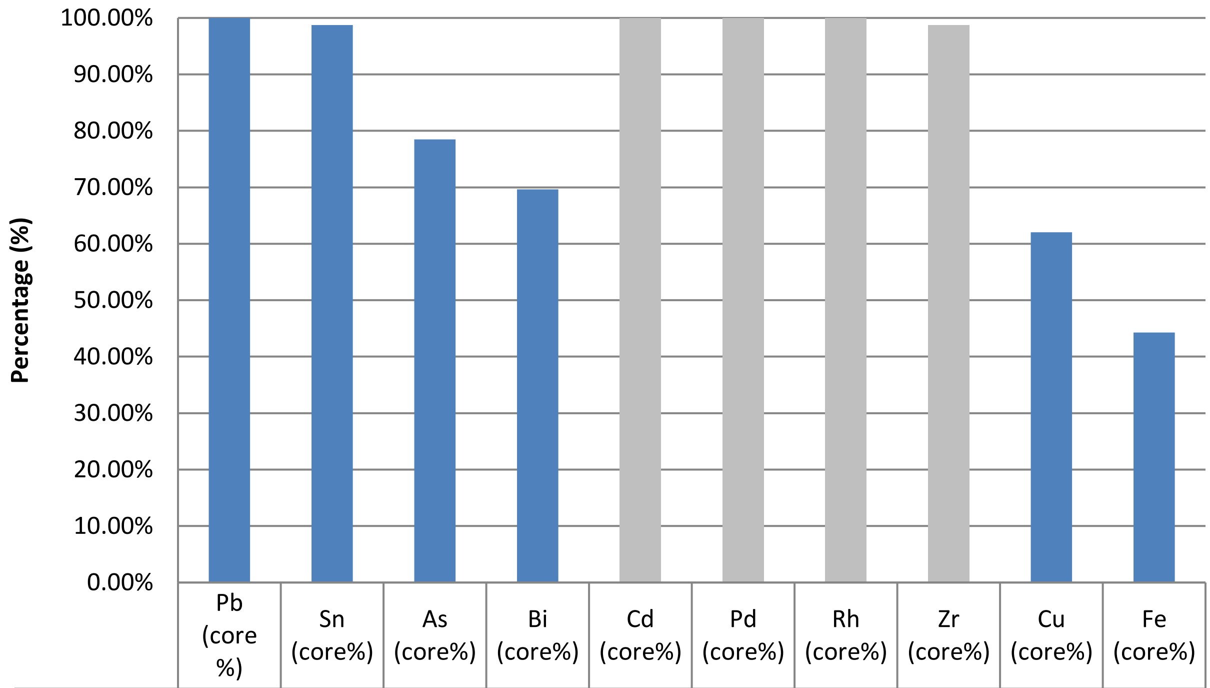


Figure 251: Lead content (%) of all 79 bullets revealing only eight bullets to have a lead content <90%.

Lead (Pb), cadmium (Cd), palladium (Pd) and rhodium (Rh) were traced in every bullet analysed, closely followed by tin (Sn) and zirconium (Zr) which were both present in 98.73% of the assemblage (figure 252). Traces of arsenic (As), bismuth (Bi), copper (Cu) and iron (Fe) were also recorded in most bullets, as well as antimony (Sb), selenium (Se), iridium (Ir), rhenium (Re) in very small quantities. Frequency does not relate to percentage content in the majority of elements; lead has a high frequency and high percentage content (100% and 91.75% respectively), but cadmium has a high frequency and a low average percentage content (100% and 1.36% respectively). Many of these elements have been detected as a result of the X-ray tube interacting with the sample (Allen 2016, 42, Shugar and Mass 2012, 32). This explains the recording of palladium, cadmium and rhodium in every bullet; they are not relevant readings in terms of the bullet composition. It was also noted during analysis that a bismuth peak was being recorded, though this could be a Pb Mα line peak being detected as they overlap on the spectra (bismuth Mα line is 2.42, lead Mα line is 2.34).



	Pb (core %)	Sn (core%)	As (core%)	Bi (core%)	Cd (core%)	Pd (core%)	Rh (core%)	Zr (core%)	Cu (core%)	Fe (core%)
% of bullets	100.00%	98.73%	78.48%	69.62%	100.00%	100.00%	100.00%	98.73%	62.03%	44.30%

Figure 252: Percentage of bullet collections containing major elements i.e. 100% of the bullets analysed contained lead. Elements in grey are background from the X-ray tube and not part of the bullet composition.

The highest element in terms of percentage content in the assemblage is lead (Pb), with the highest reading at 96.40%, the lowest reading at 32.70% and an average percentage content of 91.75±7.54%. The second highest element in terms of percentage content is tin (Sn) which is present in 98.73% of the assemblage with the highest reading at 63%, the lowest reading at 0.54% with an average percentage content of 2.57±7.47% (table 87). However, the range of lead and tin present in the assemblage is significantly altered by a single bullet from the siege site of Wareham (WAR 43) which contains 63% tin and 32.7% lead. If you remove this bullet, the range of percentage content reduces dramatically for both lead and tin (see figures 253 and 254). The third highest element for percentage content is arsenic (As), with the highest reading detected at 4.82%, the lowest at 0.14% with an average percentage content of 2.63±1.52% (figure 255).

Element	Average content	Highest content	Lowest content
Lead (Pb)	91.75±7.54%	96.40%	32.70%
Tin (Sn)	2.57±7.47%	63%	0.54%

Table 87: Lead and tin contents of sampled bullets.

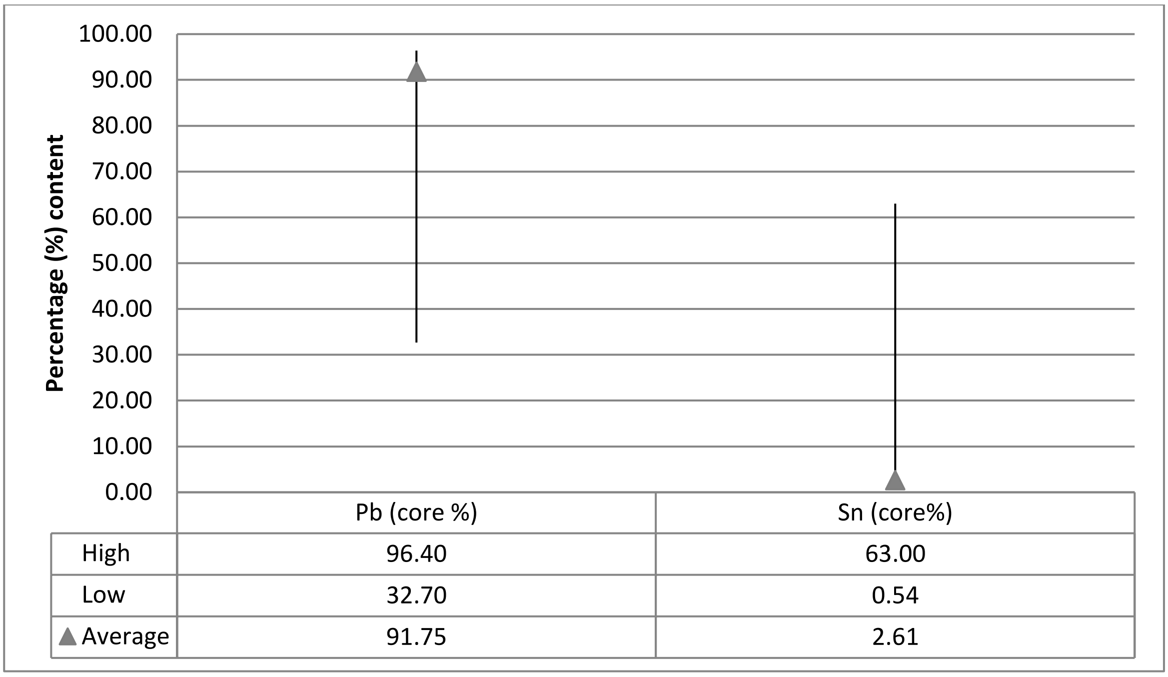


Figure 253: Percentage ranges of Pb and Sn in core of bullets analysed, showing range and average content including bullet WAR 43.

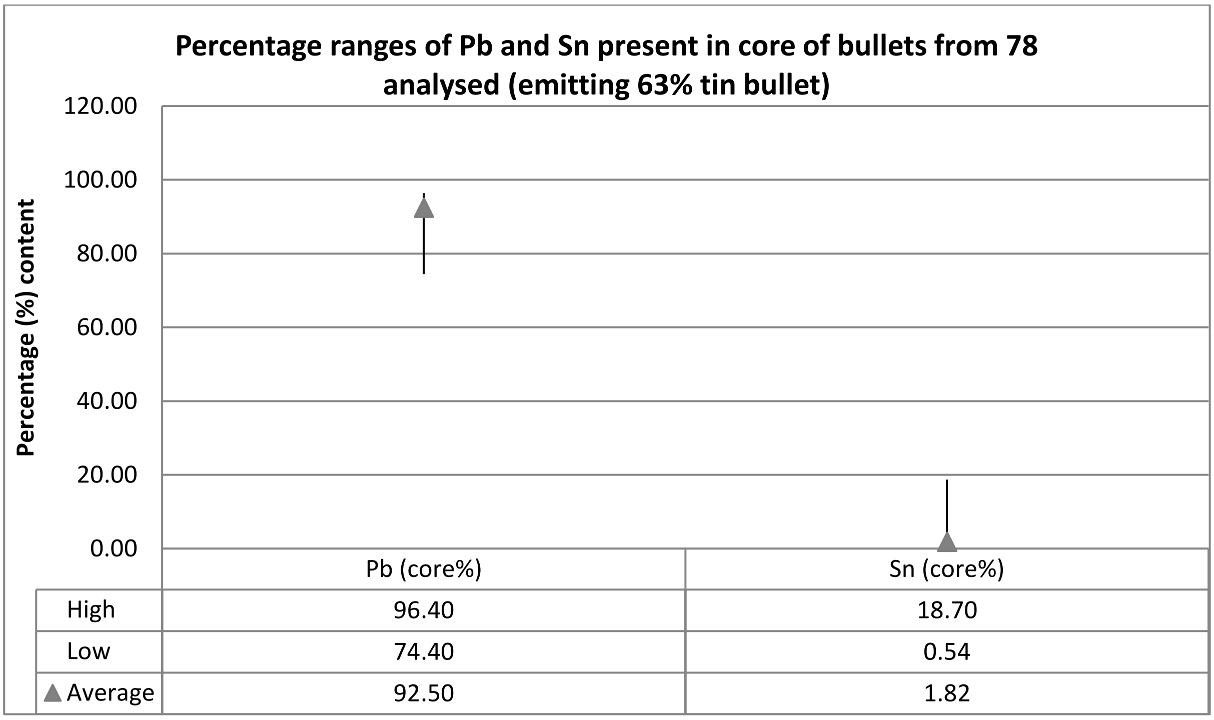
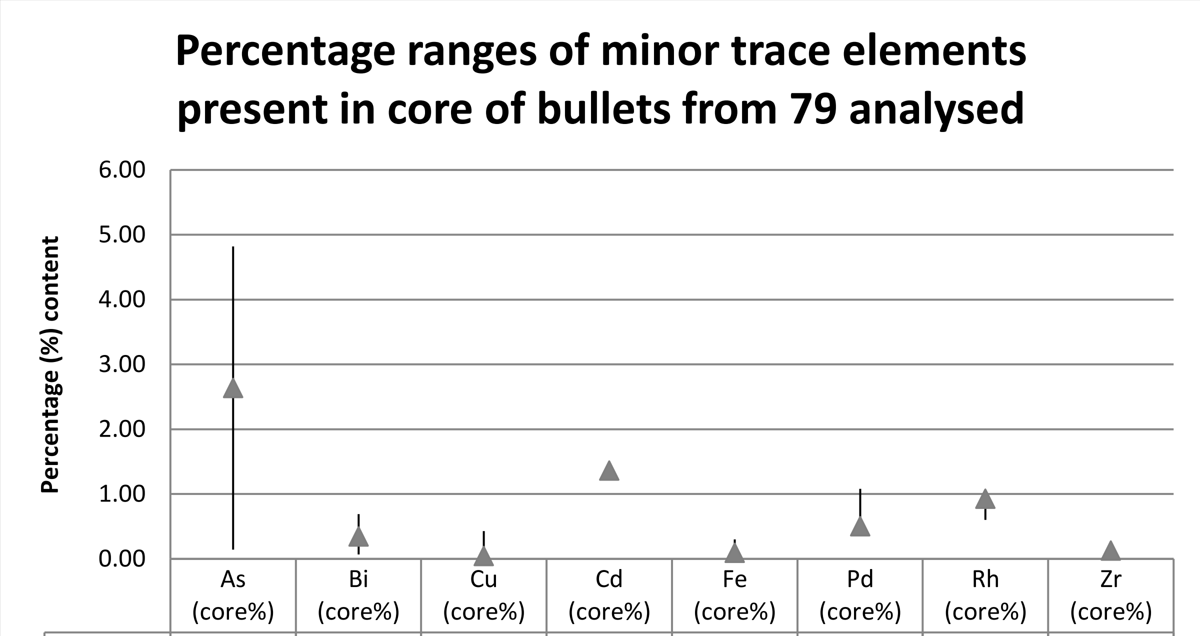


Figure 254: Percentage ranges of Pb and Sn in core of bullets analysed showing range and average content, omitting bullet WAR 43 (63% Sn, 32.7% Pb).



	As (core%)	Bi (core%)	Cu (core%)	Cd (core%)	Fe (core%)	Pd (core%)	Rh (core%)	Zr (core%)
High	4.82	0.69	0.43	1.40	0.30	1.08	1.00	0.15
Low	0.14	0.07	0.01	1.34	0.03	0.45	0.60	0.04
▲ Average	2.63	0.35	0.04	1.36	0.09	0.50	0.93	0.13

Figure 255: Percentage ranges of trace elements in core of bullets analysed showing range and average content, including arsenic and other trace elements.

90% of the assemblage analysed produced very similar XRF spectra, with high Pb peaks and small peaks of trace elements (figure 256 and table 88). If the lead content of the bullets is compared to the average condition score of the bullets, a slight correlation can be seen with decreasing preservation as lead content decreases (figure 257). This indicates that bullets with the highest lead content are generally in better condition. However, this relationship is weak and is not supported by a statistically significant correlation (table 89).

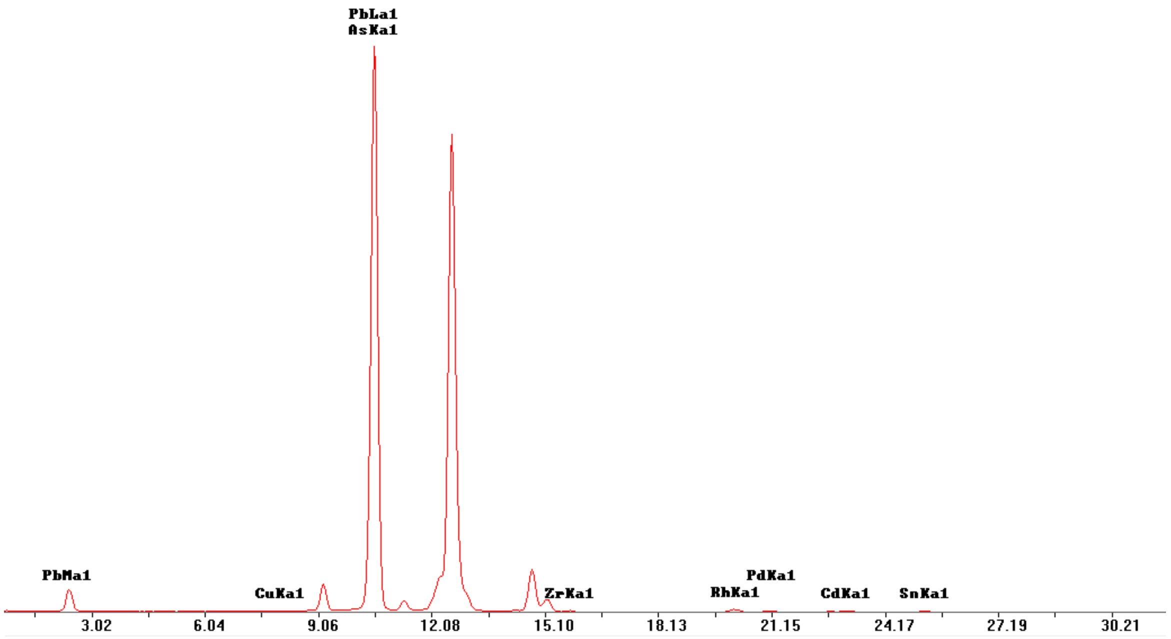


Figure 256: Sample XRF spectrum showing typical spectrum and main elemental peaks from the sampled collection (MOR 0117).

Element	Pb	Sn	As	Cd	Rh	Pd	Zr	Cu
% composition	95.00	1.01	1.00	1.35	1.00	0.48	0.14	0.03
± error	0.21	0.06	0.07	0.05	0.03	0.02	0.01	0.01
Identified position of K, L or M lines on spectrum (eV)	10.54 (la line, 2.35 ma line)	25.27 (ka line)	10.54 (ka line)	23.17 (ka line)	20.21 (ka line)	21.17 (ka line)	15.77 (ka line)	8.04 (ka line)

Table 88: Sample XRF elemental composition showing a typical spectrum for the sampled collection (MOR 0117).

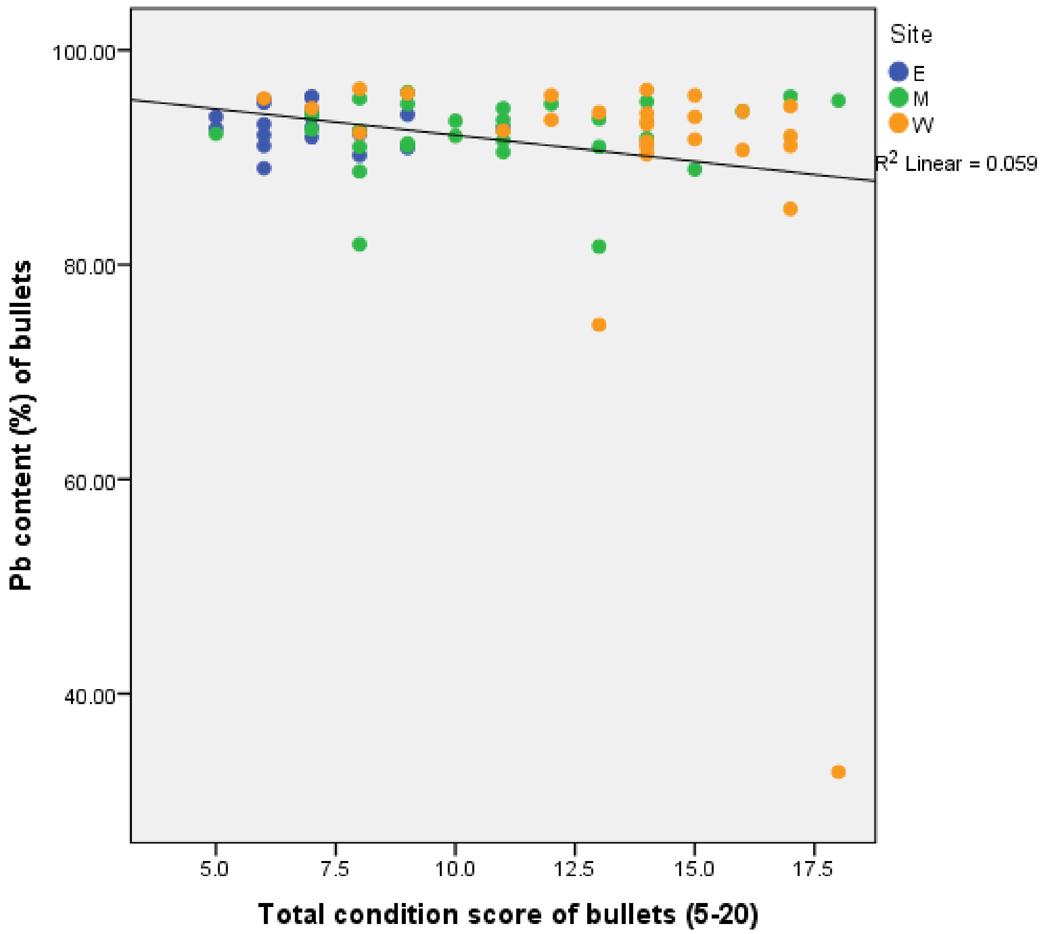


Figure 257: Scatter plot showing the relationship between the total condition score of bullets and their Pb content, showing little correlation; though that as Pb content declines, condition score increases slightly.

			Pb	Condition
Spearman's rho	Pb	Correlation Coefficient	1.000	-.116
		Sig. (2-tailed)	.	.311
		N	79	79
	Condition	Correlation Coefficient	-.116	1.000
		Sig. (2-tailed)	.311	.
		N	79	79

Table 89: Spearman's correlation of Pb content against total condition score of bullets, indicating a slight negative correlation value of -0.116 which is not statistically significant.

89.87% of the bullets (71 in total) had over 90% lead content, with only eight bullets having a composition lower than 90% lead. Tin has been identified as the second highest in percentage content after lead. These eight bullets include four bullets from Moreton Corbet, three from Wareham, and one from Edgehill; their increase in tin content corresponded with a decrease in lead content (figure 258). It is evident that, even though the majority of bullets are relatively pure lead, when the lead content does drop, there is a slight positive correlation with the tin content increasing. This pattern is observed in each of the three bullet assemblages.

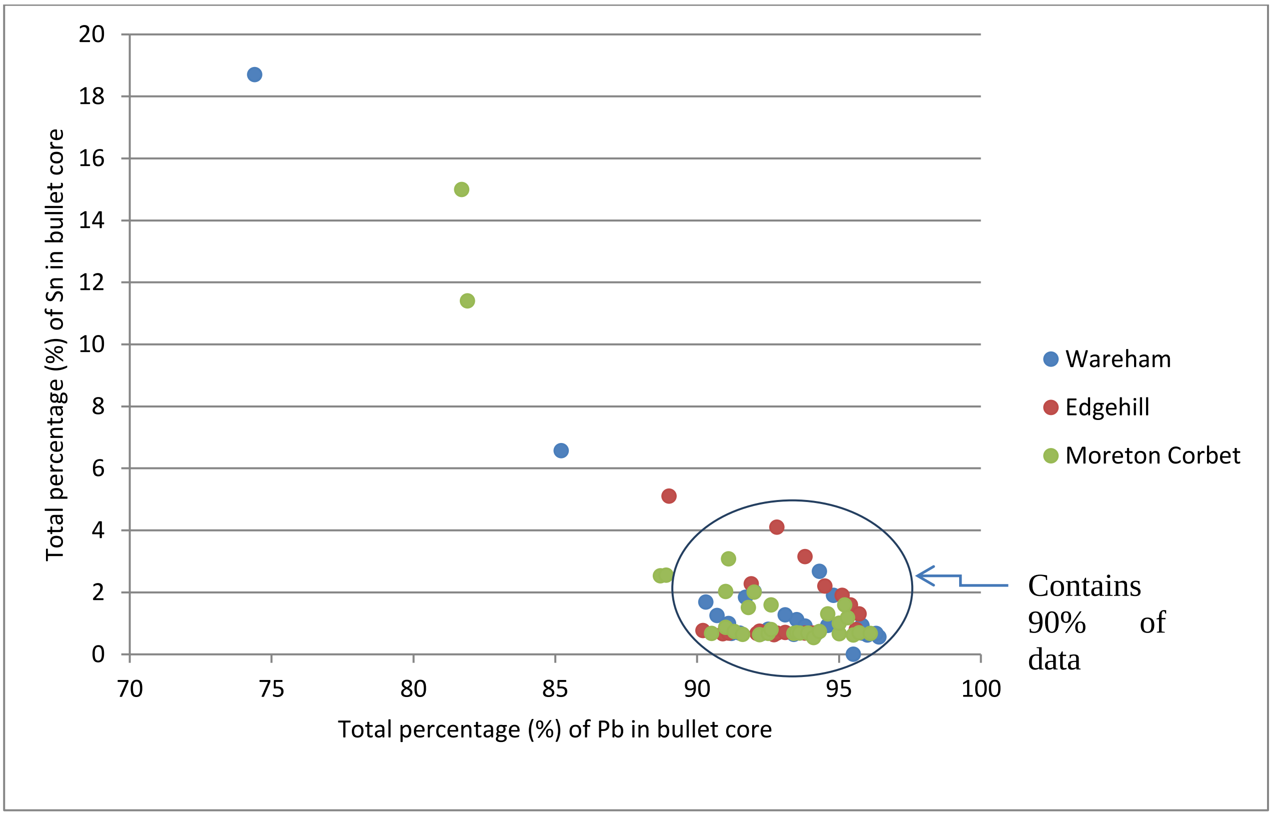


Figure 258: Percentage content of Pb and Sn of bullets from the sites of Wareham, Edgehill and Moreton Corbet. (Bullet WAR 43 has been removed from the graph which contains 63% tin).

8.3.2 The relationship between lead and tin content

Variations in lead content may be the result of different lead sources for the production of bullets. It has been shown in this study that the bullets from the battlefield of Edgehill are relatively high in lead content with few impurities (see chapter 6). Edgehill was a significant campaign in the Civil Wars involving thousands of troops and commercially produced bullets of higher quality were supplied to major field armies in large quantities. However, the sieges of Moreton Corbet and Wareham were actions involving smaller local forces, which often had to produce their own ammunition resulting in a poorer standard (Foard Pers. Comm. 01.05.2017). As at the Parliamentary garrison of Gloucester, bullets, paper cartridges and even gunpowder was made locally to maintain supplies at the garrison (Howes 1992, 37-38). The same activities may have occurred at Wareham and Moreton Corbet, resulting in occasional higher tin contents.

If the condition of all sampled bullets from this study is plotted against the tin content, there is no strong correlation (figure 259), though the correlation coefficient of 0.228 suggests a slight positive relationship suggesting condition worsens with increasing tin content (table 90). The weakness in correlation is in part due to the majority of bullets containing less than 3% tin. However, six bullets have a tin content of 5% or above (table 91). If we compare the condition of these six bullets with their condition scores, four of the bullets score a 3 or 4, and two score a 1 for very good condition, indicating that not all bullets with a moderate tin content have been poorly preserved. However, the bullets which score a 1 were recovered from areas which were either neutral to alkaline pH, or from pasture areas which will have aided in their preservation. Also, the three bullets with the highest tin contents score a 3 or 4 suggesting they have not preserved well.

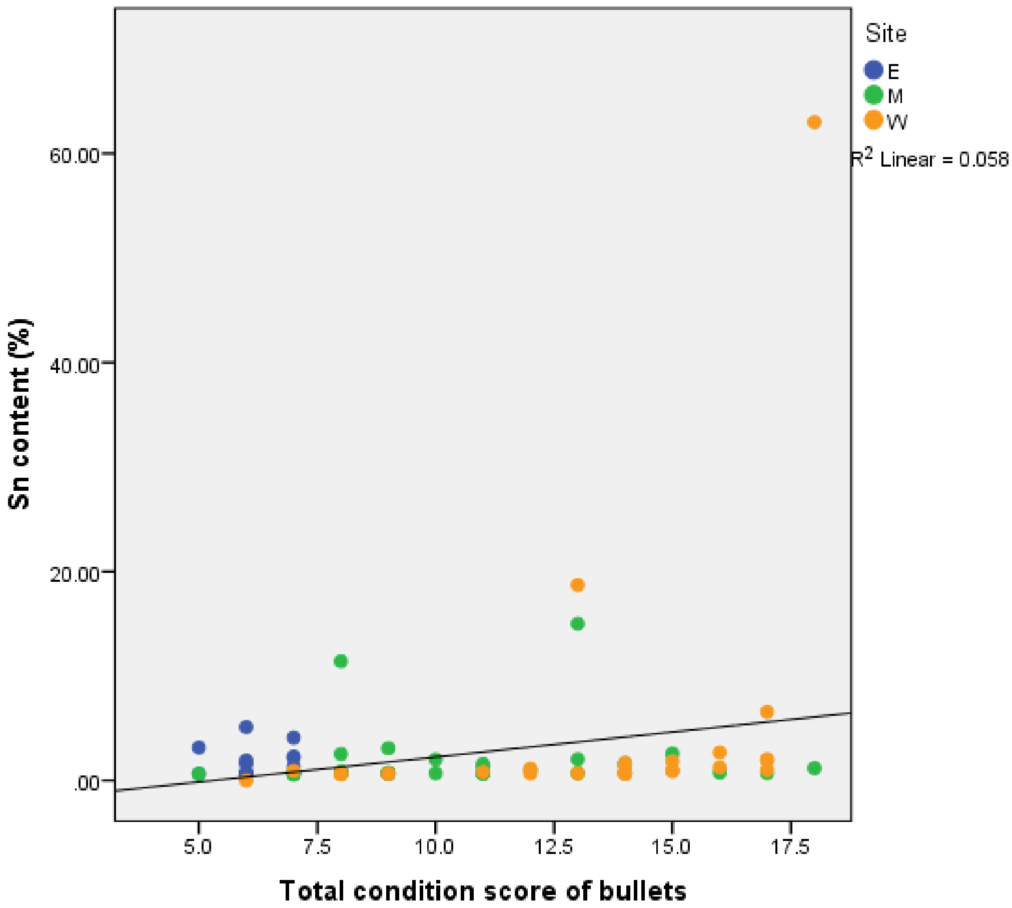


Figure 259: Scatter plot of the condition of bullets against the tin content (%) showing a slight positive correlation.

			Condition	Sn
Spearman's rho	Condition	Correlation Coefficient	1.000	.228*
		Sig. (2-tailed)	.	.043
		N	79	79
	Sn	Correlation Coefficient	.228*	1.000
		Sig. (2-tailed)	.043	.
		N	79	79

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

Table 90: Spearman's correlation coefficient for tin (Sn) content against condition of bullets. A slight positive correlation with a value of 0.228 indicates that there is a slight tendency for condition score to increase as tin content increases.

Bullet	Lead content	Tin content	Overall condition score	Average condition score
WAR 43	32.7%	63%	4	18
WAR 2219	74.4%	18.7%	3	13
MOR 0264	81.7%	15%	4	13
MOR 0014	81.9%	11.4%	1	8
WAR 1356	85.2%	6.57%	3	13
EDG 2161	89%	5.11%	1	6

Table 91: Six bullets with the highest tin content and their corresponding condition scores.

When discussing the tin content of bullets, it is interesting to note that the single bullet from Edgehill which scored 3 for fair condition has a tin content of 4.1%, the second highest tin content from the site. This perhaps suggests a correlation between tin content and poorer condition of preservation; that lead-tin alloys with a small tin content are more prone to corrosion (Sivilich and Seibert 2016, 118; Selwyn 2004, 142). It is also interesting that the bullets with the highest tin contents of 15% and above all score 3 or 4 in the condition assessment and come from the sites of Wareham and Moreton Corbet. The bullets from Edgehill are relatively pure and all contain a lead content of 89% or higher.

8.3.3 The 'barnacle' bullet

Bullet WAR 43, nicknamed the 'barnacle' bullet due to its severe corrosion, has a tin content of 63%, far higher than any other bullet analysed and is recorded as a lead-tin alloy (figure 260 and table 92). This bullet also has the highest total condition score out of all the bullets sampled for XRF analysis; a total score of 18 out of a possible 20. It is likely that the high tin content in this bullet has led to its extreme deterioration as no other bullet analysed shows such severe corrosion (figure 261). However, without more bullets in the assemblage to contain such high tin contents, it is difficult to conclude as to what tin percentage content would impact on the long term preservation of lead-tin alloyed bullets in the ground. Further analysis of bullet collections from other battlefields and sieges would build on this dataset and provide more evidence on the significance of tin content on the preservation of Civil War bullets.

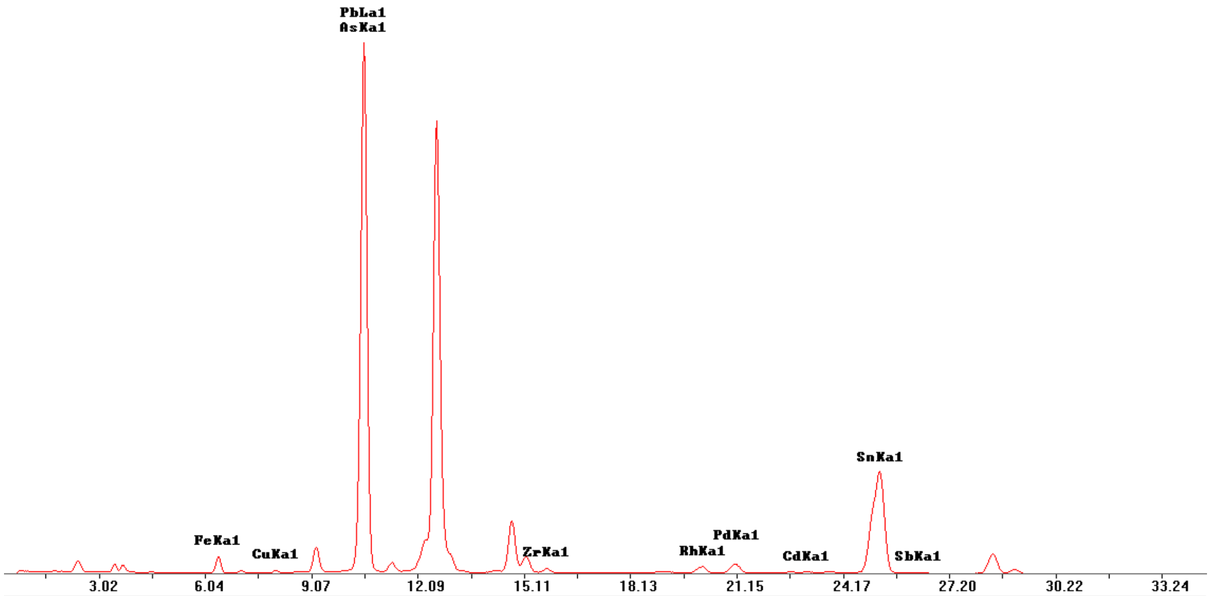


Figure 260: XRF spectrum for bullet WAR 43 showing the main elemental peaks.

Element	**Sn**	**Pb**	**Fe**	**Cd**	**As**	**Pd**	**Rh**	**Bi**	**Ti**	**Ir**	**Re**	**Zr**	**Cu**
% compos.	53.5	38.6	2.18	1.36	1.10	1.07	0.63	0.51	0.35	0.22	0.14	0.13	0.11
± error	0.22	0.10	0.04	0.03	0.04	0.02	0.02	0.02	0.10	0.03	0.02	0.01	0.01
Identified position of K, L or M lines on spectrum (eV)	25.26 (ka line)	10.54 (la line)	6.40 (ka line)	23.18 (ka line)	10.54 (ka line)	21.17 (ka line)	20.21 (ka line)	-	-	-	-	15.78 (ka line)	8.04 (ka line)

Table 92: XRF elemental composition for bullet WAR 43, showing high level of tin content.

Figure 261: Microscopic image of bullet WAR 43 showing significant loss of surface, cracks, severe flaking and loss of surface almost to the point of being unidentifiable as a bullet.

8.4 Overview of comparison data

Through analysis of each soil attribute and metallic composition of bullets across the three sites it is apparent some variables have stronger correlations than others. Several attributes have revealed little or negative correlations with bullet condition. Conductivity, water content, organic content and nitrate content all display negative correlations with condition and may affect bullet deterioration early on in the corrosion process rather than the long term. The soil parameter with the strongest positive correlation to condition of bullets is chloride content of the soil. A positive correlation coefficient value of 0.837 indicates a relatively strong trend for condition score of bullets to increase as chloride content in the soil increases. This data suggests that chloride contents should be kept relatively low to encourage the long term preservation of lead in the ground.

Another soil parameter with strong positive correlation with object condition is acidity. A correlation coefficient of -0.781 for increasing acidity with improving condition of lead bullets indicates that pH has a relatively strong impact on the preservation of bullets. All bullets in alkaline conditions of pH 7.0 and above were well preserved.

Clay content of soil also has a relatively significant impact on the preservation of the bullets, with condition improving with increasing clay content, at a coefficient value of 0.643. Clay content also reduces the number of abraded bullets present in an assemblage, as observed at Edgehill. In contrast, higher sand content increases the rate of abrasion of bullets in the ground.

Composition analysis has revealed that better preserved bullets contain slightly higher lead contents than those which showed signs of deterioration. A higher tin content appeared to encourage the deterioration of bullets, particularly for bullets with tin contents higher than 7%. It remains unclear as to what precise amount of tin is required to accelerate the deterioration of lead-tin alloys. This study presented few examples of bullets with a significantly high tin content as most bullets contained 89% lead or more. Though small amounts of tin can act as a reactive anode against a large cathodic lead sample, it is likely that small traces of tin <2% would not be enough to accelerate the corrosion of lead artefacts.

When addressing each soil attribute, it is apparent that bullets in pasture fields are consistently better preserved, regardless of the soil parameters. This suggests that land use has the most significant impact on bullet preservation. It would be interesting in future to apply the same analysis to bullets recovered from an area of acidic pasture to see whether their condition still remains very good or whether the increasing acidity has a greater impact than being under pasture. A summary is provided (figure 262) reviewing the main factors affecting the condition of lead bullets in topsoils, and their potential relative impact as shown from results provided in this study.

Figure 262: Factors affecting the condition of lead bullets in the ploughsoil. Their relative impact has been ranked on a scale from minor (green), moderate (yellow), to severe (red) based on results presented in this study.

9 Conclusions and future work

9.1 Conclusions

The aims of this project were to identify and improve knowledge on the main threats towards the survival of buried metal assemblages in ploughsoils, using lead bullets on sites of conflict as case studies. It further aimed to assess the impact individual parameters have on the preservation of lead objects and to assess the condition of lead bullets in a measurable and standardised way. The project has succeeded in achieving its objectives by: developing an artefact condition assessment; establishing a fieldwork methodology for studying sites and collecting soil samples for analysis; mapping the condition of artefacts across landscapes; and examining the relationship between the burial environment, the metallic composition of lead bullets, and the overall preservation state of lead bullets.

A systematic condition assessment was established, tested by professionals, and applied to three lead bullet assemblages, which enabled observations on variations in condition and states of preservation. This system has been an effective way of comparing the condition state of bullets from the three sites. The assessment method needs to be adapted in future to apply to other collections and metal types. During assessment, it became clear that the shape of lead bullets changes very little in the burial environment. Therefore, this data from the assessment was limited in use. However, when applied to other object types, preservation of shape is likely to be much more insightful and may address how ploughing is affecting the breaking and deterioration in shape of particular object types. Furthermore, applying the assessment to other metal types may require amendments, as iron artefacts for instance corrode by 'weeping' and fragmenting, which is not observed in lead. If similar assessments could be developed for other object types using the one devised in this project as a guide, further data from sites could be obtained, thereby increasing understanding of the condition of all metal objects from ploughsoil contexts.

Fieldwork methodology had to vary between sites in this study. Unfortunately, the site of Wareham could not be sampled fully due to its destruction through the construction of a quarry. Moreton Corbet provided the most thorough burial environment assessment, which was deemed necessary due to the variation in soil chemistry, topography, and land use witnessed across the site. The more samples collected, the better the nature of the burial environment can be evaluated. Combining soil analysis with assessment of land use history has allowed a recreation of historic and present burial environments.

This project has also mapped the condition of lead bullets across the two sites of Edgehill and Moreton Corbet. The condition of the Edgehill material was very good and no patterns of deterioration in condition could be observed, though bullets were consistently better preserved in areas of permanent pasture. In the case of Moreton Corbet, areas of good or poor preservation could be associated with topography, soil texture, and land use history.

The project also sought to identify which factors have the most significant impact on the preservation or deterioration of lead bullets, and to propose future strategies to help manage and conserve such sites for future generations. This project has shown that the degradation process is extremely complex and numerous factors come into play. This research has shown that the most significant attributes affecting preservation are soil pH, soil texture, and historic land use. Moreton Corbet also revealed the impact topography and fluctuating water tables can have on the condition of bullets. Artefacts in lower areas of the site in potentially water fluctuating environments were in worse condition than those upslope in drier soils. It is evident that factors will affect each other; for instance, the soil texture and land use will ultimately affect the rate of abrasion witnessed on bullets. Therefore it is extremely difficult to identify a single factor as having the most impact on preservation.

It is evident that the key to bullet deterioration or preservation in each case is a combination of factors working together. At Wareham, the combination of high acidity, high sand content, and almost constant cultivation has led to the increased deterioration of the assemblage. This combination has resulted in over half the assemblage being severely abraded, but take one of the parameters away and the overall effect on the bullet would no doubt change. At Edgehill, the combination of alkaline clays in long term pasture has prevented the deterioration of the bullets. This indicates that one factor cannot always be identified as the single reason for the deterioration or preservation of assemblages.

Bullets residing in soil conditions of pH 7 or above were consistently better preserved than those in acidic contexts. However, even when conditions reached a pH of 4.86 at Edgehill, this still did not seem to compromise the lead patina on bullets. Bullets at Wareham in soil conditions of pH 4.46 witnessed severe corrosion. Both sites have very different soils and historic land uses, but it may be that clay requires a more extreme level of acidity to impede the preservation of lead. Bullets were better preserved in conditions where soil clay content was 30% or above, and when soil sand content was 20% or lower. Tin content appears to play a minor role in the condition of the bullets compared to soil attributes, though there is a trend for bullets to be in better condition when their tin content is lower than 7%. However, in most cases it is the combination of several attributes which affect the overall preservation of lead bullets and one single factor cannot be identified as the main indicator of decay. Parameters promoting best preservation for lead bullets based on the data obtained in this study are summarised in table 93.

However, when addressing all three case studies, the most significant attribute to affect bullet preservation appears to be land use history. All bullets were consistently better preserved in pasture fields than in arable fields. It appears bullets are better preserved in pasture regardless of other soil attributes as even when pasture resides in acidic soils of c.5.5 at Moreton Corbet the preservation is still good. Similarly, bullets are still well preserved in pasture when chloride levels are at moderate levels. When clay content falls below 20%, condition of bullets on pasture still remains very good or good. This suggests that land use has a greater impact than any other soil attribute. Furthermore, fields which have been pasture and have recently been converted to arable have seen deterioration in their condition, if only slight. Fields at Edgehill which have been converted to arable since the 1980s contain less well preserved bullets than fields that have remained under long term pasture since at least the 18th century. Bullets at Moreton Corbet which have only recently been subjected to the plough remain in very good or good condition, suggesting that several ploughing episodes are required before the effects are evident in the material record.

Long term pasture is widely recognised as the best possible form of land use for the preservation of archaeological monuments, due to the shallow rooting nature of grass which causes little soil disturbance (Darvill and Fulton 1998, 174). This project has also shown that long term pasture is the best environment for the long term preservation of buried archaeological lead artefact assemblages. It is worth in future assessing similar collections in more extreme environments of very acidic conditions in order to assess whether increasing these soil levels would affect the condition of bullets in pasture fields. Gaining more data from long term pasture sites and long term arable sites would also be beneficial to strengthen the conclusions made in this study.

The results of this research have implications for how battlefields and ploughsoil assemblages should be managed in future. It is clear that battlefields and siege sites do not benefit from enough protection from agricultural threats. A greater understanding of the nature, size and potential of buried assemblages on such sites needs to be sought in order that these buried assets are not lost to decay or through lack of knowledge of their research potential.

Few sites of conflict have been systematically surveyed. To improve our understanding of these sites, further surveys need to be carried out in order to assess their potential and survival rates, in conjunction with assessing their burial conditions. Furthermore, siege sites need to be identified as a significant historic site type and should be incorporated into a register such as the Register of Historic Battlefields 1995, which currently does not accommodate siege sites. A lack of recognition of the significance and potential of this site type is a factor which makes them even more vulnerable to loss, decay, or illicit detecting. It is worth considering restricting access to detecting on sites of conflict to those carrying out systematic and approved research surveys. Further guidelines and resources should be made available by heritage professionals on how to approach metal detecting surveys on sites of conflict.

Where possible, agricultural processes which disturb large areas of ploughzones such as deep ploughing, sub soiling and potato trenching should not be carried out on sites of conflict. This research has shown that lead bullets are best preserved in areas of long term pasture. Therefore, sites under these conditions should be retained as such. Where sites are identified as being under threat from agricultural activities, steps should be taken to convert the land to pasture, as far as practicable, for the *in situ* preservation of the buried assemblages. For sites identified as residing in damaging environments where *in situ* preservation is not a feasible option, for instance in extremely acidic or sandy regions, steps should be taken to accurately record and retrieve assemblages before further damage is caused to the artefacts.

It is recommended that Historic England review how they assess 'threats' to the preservation of archaeological sites with buried assemblages. Developmental and agricultural threats are considered as part of Heritage at Risk, but the effect environmental and soil conditions have on the survivability of below-ground artefacts are not understood, nor fully considered in current risk assessments. Further recognition of the impact of the burial environment on preservation is required. This research has shown that soil conditions can have a major impact on the preservation of buried metal assemblages, which remain the primary archaeological data on British sites of conflict.

Parameter	Level
Soil pH	>4.8 in clay, >5.5 in sands
Chloride content	<90-100mg/kg
Soil clay content	>30%
Soil sand content	<20%
Bullet tin content	<7%
Land use	Long term pasture
Abrasion	Reduced in clay soils
Topography	Upslope
Depth in soil	As deep as possible (base of topsoil)

Table 93: Summary of parameters which promote best preservation of Civil War lead bullets in the ploughsoil.

9.2 Future work

This project has highlighted the main issues and threats facing the survival of buried lead bullets in the ploughsoil. It has highlighted gaps in knowledge and identified many areas for further research and has provided suggestions for how archaeological mitigation strategies could be designed for sites in future.

This project sought to design a condition assessment to assess the preservation of artefacts in the ploughsoil. Civil War lead bullets were used as an object type to develop this, though in future this method needs to be expanded and applied to other object types and ploughsoil assemblages. Lead bullets are the primary evidence from battlefield sites, but copper alloy and iron artefacts are highly prevalent in other sites with ploughsoil assemblages. This project is the first step in ploughsoil analysis which must be extended to other landscapes and assemblages to assess the effect burial environments have on entire ploughsoil assemblages, not just one artefact type.

Evidence from Edgehill and Moreton Corbet has indicated that preservation improved in areas of long term pasture. However, no data could be collected in this study from areas of acidic pasture. Metal detecting is often only carried out on arable land with landowners' permission, and identifying permanent pasture sites proved difficult. Obtaining data from an acidic site containing areas of permanent pasture would reveal whether pH had a more significant impact on the preservation of bullets than the historic land use of the site.

Soil sampling was limited at the site of Wareham and in future studies it would be beneficial to select sites which could be more thoroughly assessed for soil conditions across the entire site. In addition, this study used soil samples collected from a single sampling procedure and in future soil samples should be collected systematically throughout the year to assess whether significant change occurs in soil conditions. The quantity of samples required by such a strategy would have been beyond the capabilities of the current project.

Sites with a clearer land use history need to be sought for future analysis. The land use history of Moreton Corbet proved to be surprisingly complex and sites need to be identified in future which provide simple, clear histories of long term arable and long term pasture use for more distinct comparisons to be made.

Moreton Corbet revealed that potentially fluctuating water tables can have a damaging impact on the preservation of lead bullets. This study did not measure water table levels systematically, but in similar future studies it is recommended that water tables should be monitored throughout the year to measure their depth and changes in depth. This would indicate whether lead bullets in the ploughsoil reside above the water table or whether they are being constantly re-wetted and dried out throughout the year which could have a detrimental impact on their condition.

One aspect of the burial environment touched upon when assessing the site of Edgehill was the oxygen content of soils. One reason for their good preservation may be down to the restricted oxygen flow through the tightly packed clay particles. A lack of oxygen would impede the ability for corrosion to take place. In future, soil oxygen levels could be assessed in order to compare oxygen levels between soil types on different sites (Cary and Holder 1982, 157; Caple 2004; Rowell 1994, 109).

Recording the depth of artefacts retrieved through metal detecting is not common practice. This could provide useful information and could be correlated with the preservation of materials. For instance, artefacts from the battlefield of Edgehill were shown to be in very good condition in this study. Several fields in the landscape are under long term pasture and as a result all the bullets have migrated to the bottom of the ploughsoil. The depth is a factor in helping to preserve artefacts away from oxygen flow at the top of the ploughsoil, but systematic recording of object depth must become a standard procedure in metal detecting surveys for this analysis to be carried out. This could be a deciding factor in how objects preserved well in pasture fields.

During condition assessment of bullets it was difficult to identify damage marks from ploughs and agricultural machinery. An experiment involving placing a number of bullets into the topsoil and having the area ploughed over a number of cultivation cycles and then analysing any marks and damage inflicted in the bullets could aid in future identification of such marks.

Chloride levels in soils appear to have a damaging effect on artefact condition, though it remains unclear as to what concentrations are required to inflict damage and accelerate corrosion. In order to assess this threat, controlled simulated experiments should be carried out in laboratory conditions in order to separate the effects from other soil parameters in the ground. A number of experiments should be carried out on patinated and unpatinated bullets to assess damage inflicted by fertilisers on essentially protected and non-protected bullets. Soil boxes could be created and different common fertilisers could be applied to each sample and left over a period of time to later assess the corrosion formed on each bullet. This would give an indication of how long fertilisers take to influence corrosion of bullets and which fertilisers and concentrations of chlorides are most damaging to the artefacts.

This research has shown that assemblages on battlefields are vulnerable to the effects of ploughing and cultivation, particularly on acidic sandy soils which cause corrosion and abrasion of lead bullets in the ploughsoil. It is worth considering protecting battlefields in such environments by restricting ploughing or converting them to pasture so further damage and data loss can be restricted. Sites under alkaline clay appear to be less vulnerable to the effects of ploughing, but fields of permanent pasture must be retained and remain out of cultivation to promote the condition of buried lead artefacts. The battlefield of Edgehill has shown that the excellent preservation of lead bullet surface details has been preserved by keeping the majority of land in use as pasture, and condition of bullets is starting to deteriorate in areas that have been converted to arable since the 1970s. Cultivation only increases the deterioration of bullet condition and their surface details, as shown at the site of Wareham. To preserve these buried artefact resources for the future, areas of pasture need to be maintained and some areas of arable land should be converted to pasture on battlefield sites to promote their long term conservation and protection.

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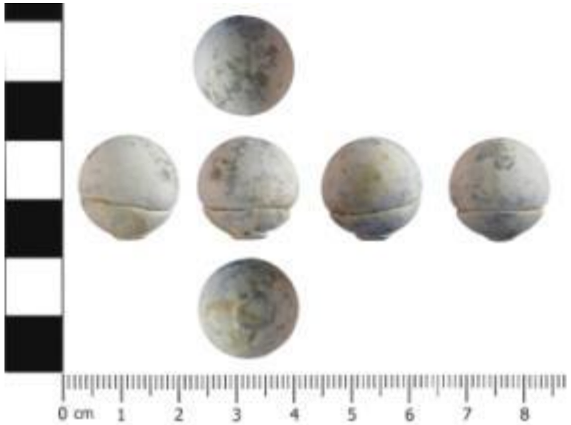
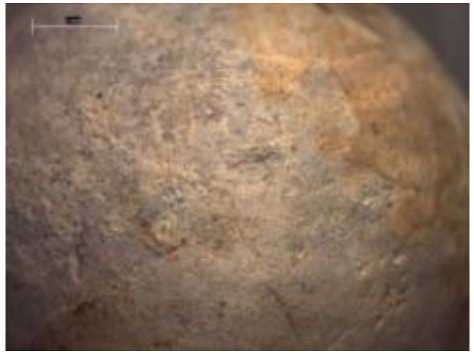
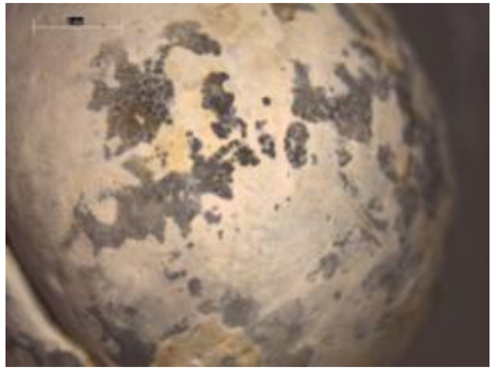
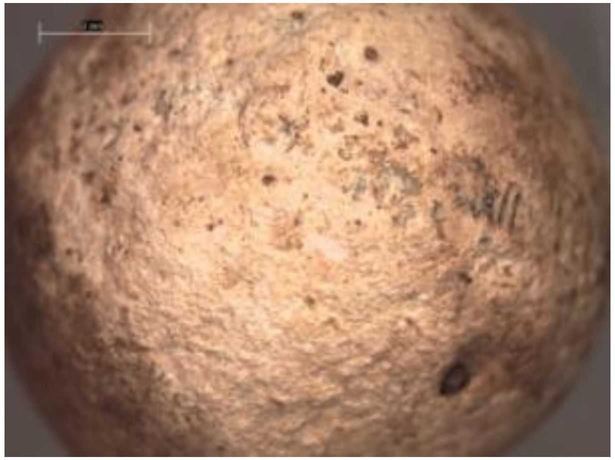
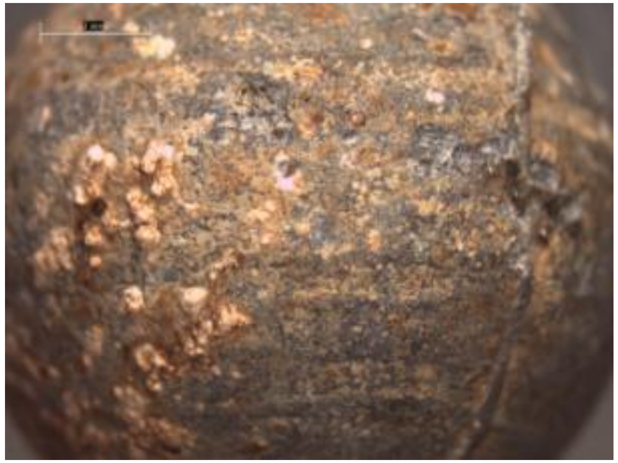
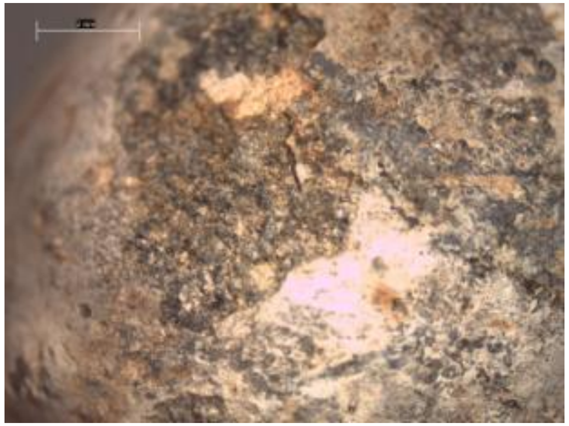
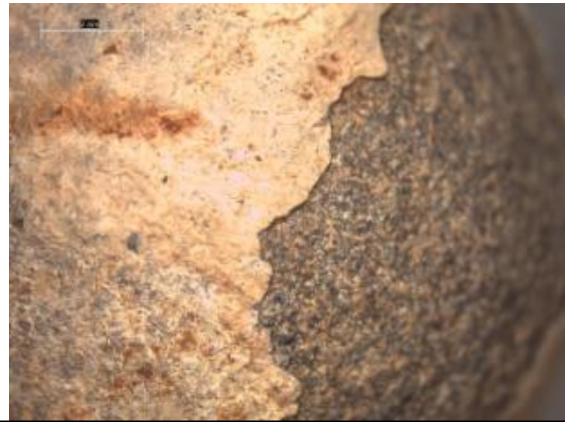
Appendices

Appendix I - Condition assessment worksheet

Score (overall)	Condition	Description	Photograph	X10 magnification of surface
1	Very Good	Surface intact, solid patina, surface details clear	 	 

2	Good	Majority of surface intact, some possible surface loss, surface details quite clear, possible corrosion obscurity		 

3	Fair	Broken patina, some surface loss, majority of details unclear, possible corrosion obscurity, cracks, and localised corrosion		 

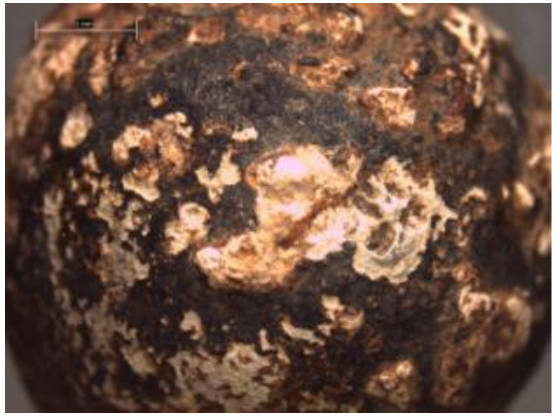
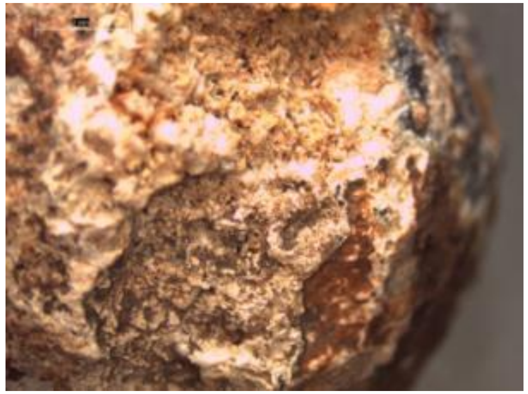
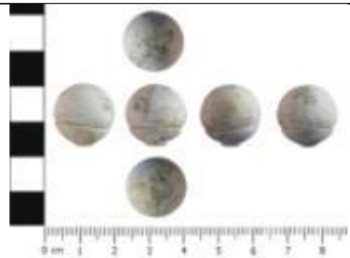
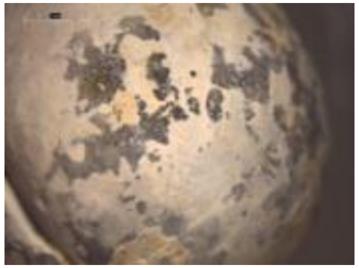
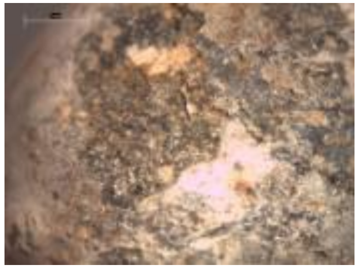
4	Poor	Broken patina, significant loss of surface, details very unclear or illegible, corrosion obscurity, cracks, and localised corrosion	 	 

Table 94: Condition assessment worksheet

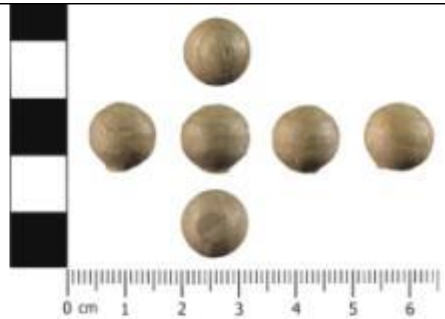
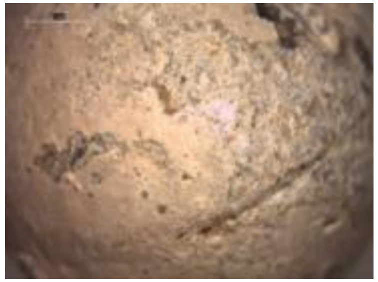
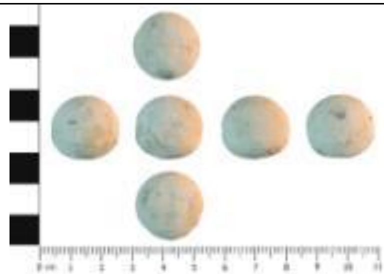
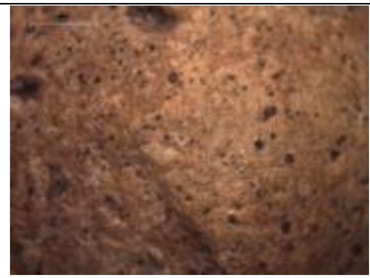
Surface condition assessment categories

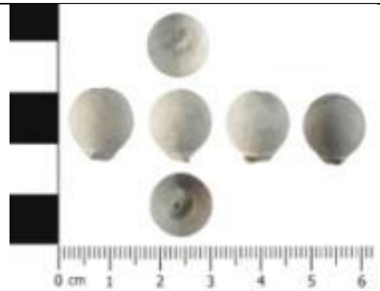
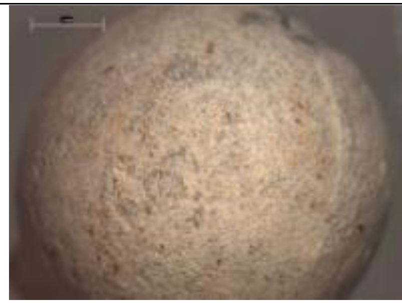
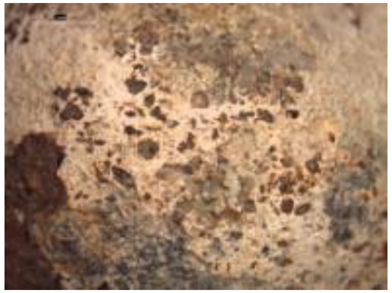
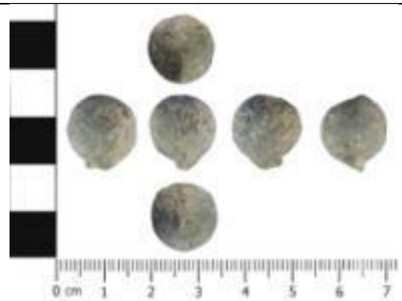
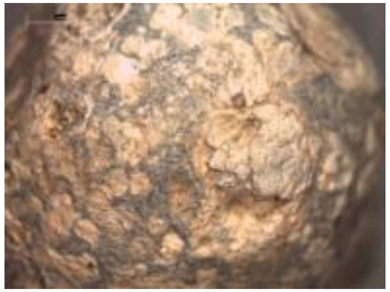
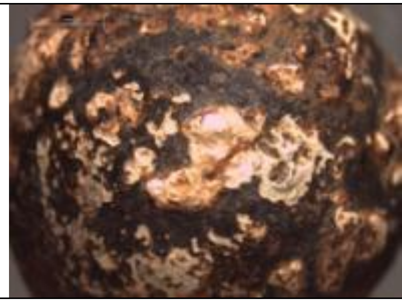
Category	Description
Smoothness of surface (SS)	Describes how smooth in touch and appearance the surface of the object is. The smoother the surface, the less pitting has occurred and the better preserved. Bullets which have significant localised corrosion, pits or globules should be noted.
Preservation of shape (S)	Describes the surviving shape of the object in terms of completeness. If an object is complete and hasn't suffered any loss of shape from being hit or damaged in the ground it will score a 1. If it has been compacted, bent, clipped or chewed it will score lower. This does not include change in shape prior to burial (e.g. impacted bullets).
Visible surface detail (SD)	Describes the clarity of surface information and features on the object in terms of visible details (cast seams, sprues, banding etc.)
Amount of corrosion products (CP)	Gives an indication of the amount of corrosion on the surface of an object. An object with a fairly consistent single coloured surface will score low but an object with several different corrosion products on the surface which is obscuring detail will score higher.
Stability of surface layer (ST)	Describes the stability of the surface layer as opposed to the underlying metal. Low scores are given if the surface has formed a solid patina. Higher scored will be given if the surface layer has been partially lost, the patina has faults or is flaking, powdery, or eroded (signs of active corrosion).

Table 95: Description of condition classes.

Parameter	Description	Score	Photograph	X10 magnification of surface
1. Smoothness of surface (pitting) (SS) Is it smooth or rough?	Majority of surface is smooth, little evidence of pitting	1		
	Fairly smooth surface, some pitting on surface, possible globules/warts of localised corrosion	2		
	Fairly rough surface with substantial pitting/warts penetrating surface	3		
	Rough uneven surface with majority of surface pitted/warts, penetrating surface	4		

2. Preservation of shape (S) (completeness-post depositional)	Object is complete with little change in shape	1	
(compacted, chewed, clipped, bent)	Some damage to shape, possible breaks or deformities	2	
	Deformed or significant loss to completeness of object	3	
	Majority of object lost/incomplete/deformed	4	

3. Visible surface detail (wear/erosion, clarity) (SD)	Surface detail clear	1		
	>50% surface detail visible	2		
	<50% surface detail visible	3		
	No or minimal visible details	4		

4. Amount of corrosion products (obscurity) (CP)	Few corrosion products mainly consisting of stable surface layer	1		
	Some corrosion products <50% of surface obscured	2		
	Many corrosion products present, possibly showing layers and obscuring >50% of surface	3		
	High level of corrosion products obscuring majority of surface	4		

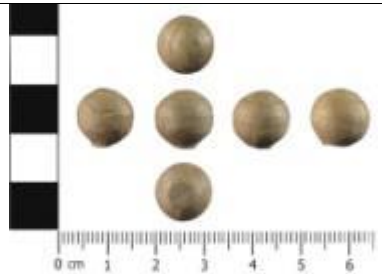
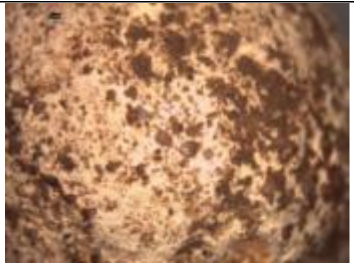
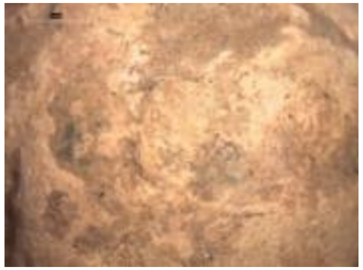
5. Stability of surface layer (solidity/ softness or loss of surface) (ST)	Unbroken patina, stable hard solid patina covering surface of object	1		
	Stable hard patina over surface with some failures/chips and possible loss of surface	2		
	Majority of surface damaged or lost, partial eroded sandy surface and localised corrosion	3		
	Friable sandy surface, almost entire loss of surface and signs of active corrosion (powdery, soft, friable, sandy)	4		

Table 96: Condition assessment worksheet for five condition categories.

Appendix II- Malvern Mastersizer 2000

The Malvern Mastersizer (Malvern Instruments Ltd) is a laser diffraction particle size analyser. This technique was introduced in the early 1970s and in the last few decades laser diffractometry has been increasingly used to analyse a variety of sediments as an alternative to sieving and sedimentation (Miller and Schaetzl 2011, 1720; Sperazza, Moore, and Hendrix 2004, 736). The Mastersizer is designed for measuring particle sizes in the range 0.02 - 2000µm and therefore comfortably covers all the soil particle size classes (Storti and Balsamo 2010, 26). It works on the principle that particles of a given size diffract light at a given angle. The system passes a laser beam through a suspension and measures the angle and intensity of the diffracted light by the particles within the given suspension. The light energy diffracted by the suspension circulating through the cell is measured by 52 sensors and compared against known size distributions using phi and µm graduations using Fraunhofer or Mie theory (Dias 2014; Storti and Balsamo 2010).

Goossens (2008) tested 10 different particle size distribution methods and concluded that there is no single optimum technique to measure grain size distributions, through laser diffraction techniques tend to produce the best results. Although the International Organisation for Standardisation considers the pipette method the standard form of analysis, this techniques is slow and does not always show good reproducibility (Goossens 2008, 68). There is ongoing debate as to the accuracy of laser diffraction results, especially regarding their direct comparison to more traditional methods. Variability in results can result from sample preparation methods, properties of the sediment, removal of organic matter, and the machine parameters including pump speed, use of ultrasonication, use of dispersant, measurement times, and the chosen refractive index and absorption (Miller and Schaetzl 2011; Sperazza, Moore, and Hendrix 2004; Vdovic, Obhodas, and Pikelj 2010). Sample preparation and choosing optimum machine settings is essential for accurate particle size distribution analysis.

Optimisation of the machine requires trials and testing several elements. Pump speed can affect the circulation and suspension of the varying particle sizes. With too low a pump speed the coarser sediment will start to settle at the bottom of the beaker and will create a bias measurement towards finer particles. Optimal pump speed for effective circulation of soil is around 2000 rpm (Sperazza, Moore, and Hendrix 2004; Storti and Balsamo 2010). Dispersion agents are not always added to soil-water suspension, especially for coarser sandy samples, but for clay samples which may have a tendency to flocculate it is advised to use sodium hexametaphosphate to avoid particles binding together and appearing as larger particles to the machine (Dias 2014; Sperazza, Moore, and Hendrix 2004). Ultrasonication is intended to agitate and restrict flocculation of clay particles. As opposed to sand particles which tend to be spheroid, clays are plate-like in shape and therefore have a high surface area-to volume ratio and have a tendency to flocculate and agglomerate (Brady and Weil 2002, 134; Sperazza, Moore, and Hendrix 2004, 738). Applying ultrasonication will help prevent this process, but overuse can lead to the breakdown of large particles within the fraction.

Research has suggested that laser diffractometry can underestimate the proportion of fine clay and silt particles in a soil fraction (Campbell 2003; Vdovic, Obhodas, and Pikelj 2010, 859). This is due to the fact that the laser will indirectly measure particle size based on the assumption that particles are spherical. The laser sees particles as two-dimensional and gives a grain size based on the cross section of the particle. Clays are plate-like in formation and can have a diameter of 2µm, but a length of up to 10µm. Work by Konert and Vandenberghe (1997, 533) suggests that the standard 2µm grain size for clays when using pipette methods corresponds to a grain size of 8µm when using laser diffractometry. Therefore, in this research clays will be allocated a maximum size cut off point at 8µm in order to prevent misinterpretation of results.

Sperazza *et al* (2004) summarise the optimal set up and conditions for analysing soils using laser diffractometry (table 97), though others suggest slight variations. Storti and Balsamo (2010) suggest absorption of 0.1 and a refractive index (RI) of 1.6, though a RI of 1.53-1.57 is most commonly used for soil analysis. It is suggested that sample preparation and pump speed have a much greater impact on results than refractive index and absorption settings and through initial tests in this study this was found to be the case (Konert and Vandenberghe 1997).

Parameter	Setting
Obscuration	15-20%
Pump speed	1800-2300 rpm
Absorption	1.0
Ultrasonication	60 seconds
Dispersing agent	Sodium Hexametaphosphate 5.5g/l for up to 24 hours

Table 97: Optimum settings for analysing soil texture using laser diffractometry, devised by Sperazza, Moore and Hendrix (2004).

Appendix III– XRF and XRD theoretical background

X-ray Fluorescence

X-ray Fluorescence (XRF) is a standard technique for identifying the chemical nature of an inorganic artefact (English Heritage 2008, 12; Shugar and Mass 2012, 19). X-rays have been in use for commercial analysis since the 1950s and archaeologists are now one of the main buyers of portable instruments (pXRF) (Shackley 2011, 7, 11). XRF identifies major and trace elements in materials by detecting their behaviour when they interact with radiation. The process involves an X-ray beam illuminating a sample, which then becomes excited. The atoms in the sample absorb a portion of the X-ray energy, causing an electron to be expelled and replaced by an electron from a higher energy band. The most frequent transition to occur is an electron being replaced in the K-line by an electron from the L-line in the atom, through the photoelectric effect (figure 263) (Shackley 2011, 17). This release of energy creates photons which are then detected by the instrument and can be identified based on the chemical properties of the sample (Seibert *et al.* 2016, 144). The amount of absorption that occurs depends on the thickness of the sample, constituent elements, and the wavelength of the X-rays; lead has a relatively high degree of X-ray absorption (Malainey 2012, 478).

XRF has benefits in that it is relatively easy to use, results are produced quickly, samples require minimal preparation, and is theoretically non-destructive (Shackley 2011, 8). However, it does have limitations. The instrument is surface sensitive and only takes measurements from the uppermost 100μm of the sample and so does not give an accurate representation of the underlying metallic composition (Pollard 1985, 27; Malainey 2012, 483). Surface measurements can be distorted by corrosion patination, and unprepared samples may be affected by weathering and other forms of contamination; even a thin layer of oxidation may alter the compositional results (Shackley 2011, 9; Malainey 2012, 483; Shugar and Mass 2012, 29). It detects heavy elements, but struggles to detect elements lighter than Al (Shugar and Mass 2012, 26). It works best on metals which are flat, clean and homogenous and it is rare to get such a sample from an archaeological context. Ideal samples would be ground to a fine powder for the best results (Dobby 2016, 4).

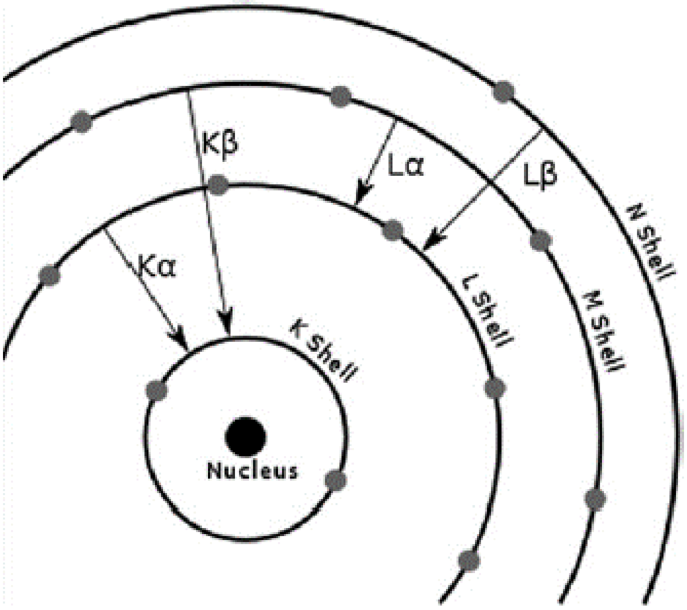


Figure 263: View of orbital transitions due to X-ray fluorescence with electrons being replaced from higher energy bands (Shackley, 2011, p. 17).

X-ray Diffraction

The chemical composition of an artefact can be determined by X-ray diffraction (XRD) and is very useful for identifying corrosion products formed on artefacts (English Heritage 2008, 13). The composition is determined from the diffraction pattern obtained when a crystal structure is irradiated with an X-ray beam. Each mineral has a unique composition and therefore a unique lattice structure. How a mineral diffracts an X-ray beam depends on the spacing and arrangement of the atom in this structure (Malainey 2012, 479). When X-rays hit a sample, some are reflected off the surface whilst others penetrate and reflect off planes of atoms within the structure (figure 264). The path of the X-rays depends on the angle of incidence. The entering and exiting X-ray is always at the same angle, but the X-rays may travel different distances. The distance between parallel planes of atoms within the structure is related to the object's composition. The diffraction of X-rays can be calculated using Bragg's equation to determine what elements or compounds are present in the spectrum:

$$\lambda = 2d\ sin\theta$$

n= order of diffracted beam

λ= wavelength (nm)

d= lattice spacing (nm)

θ= diffraction angle (degrees)

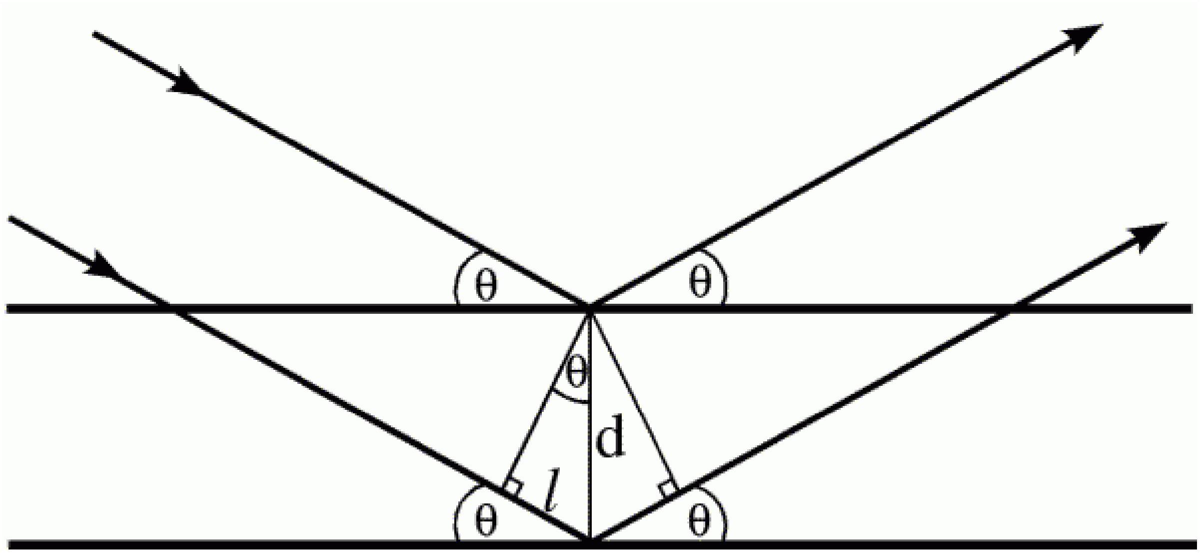


Figure 264: Diffraction of x-rays by a crystal: d sin θ is travelled both before and after diffraction, for a total distance of 2d sin θ. Adapted from Malainey (2012, 480).

Appendix IV- XRD spectra for lead and tin compounds

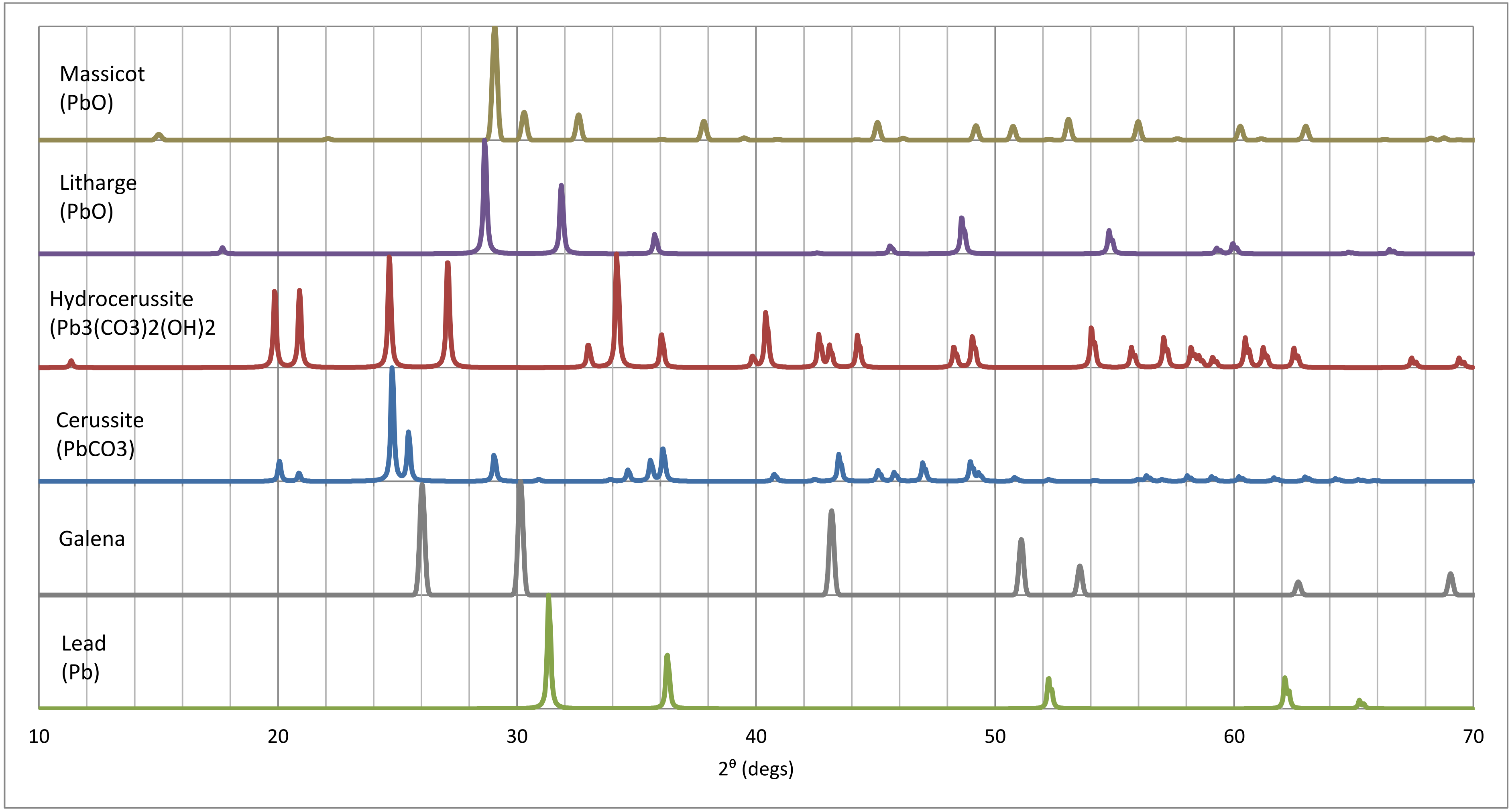


Figure 265: Common lead compounds part 1.

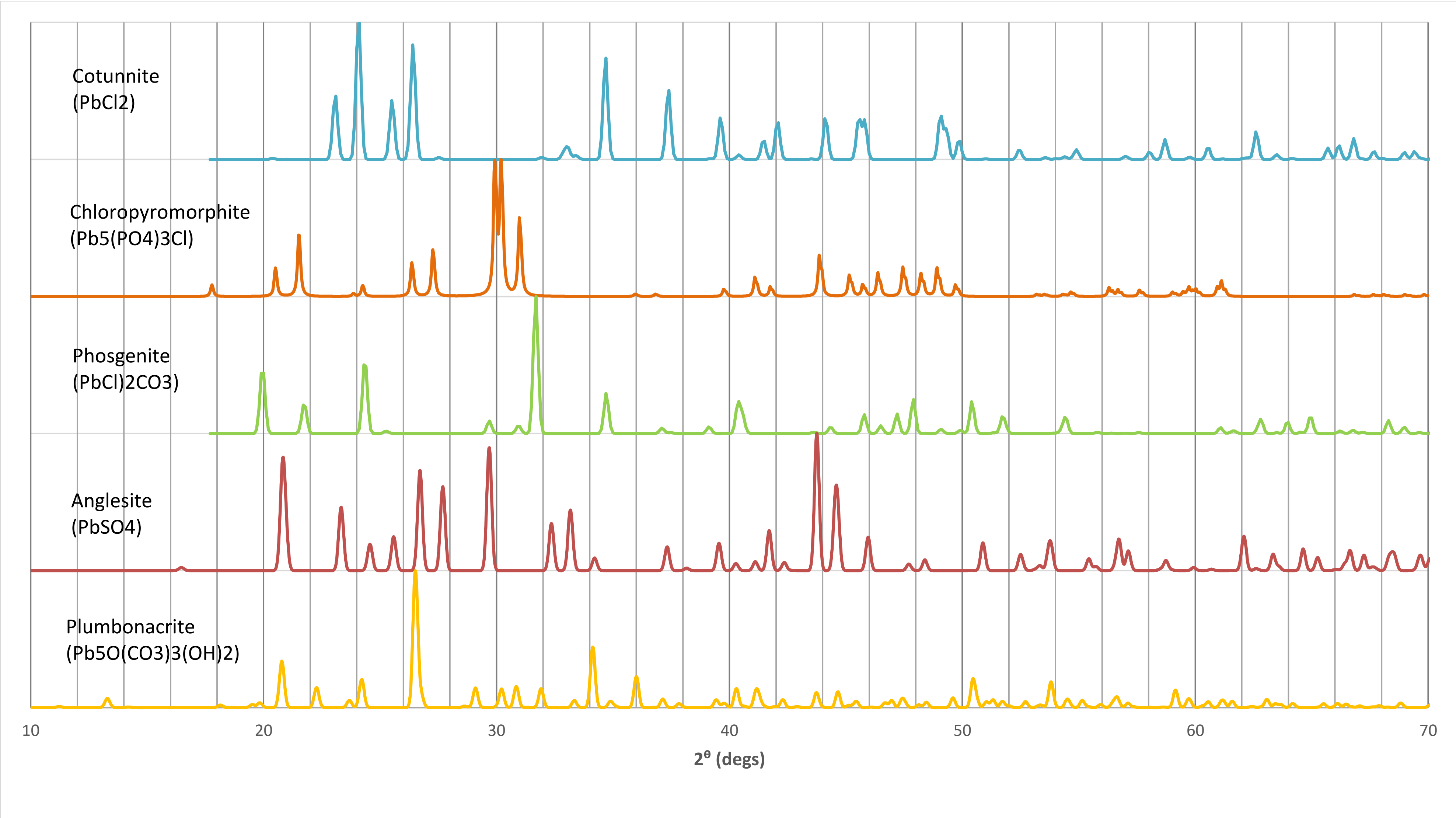


Figure 266: Common lead compounds part 2.

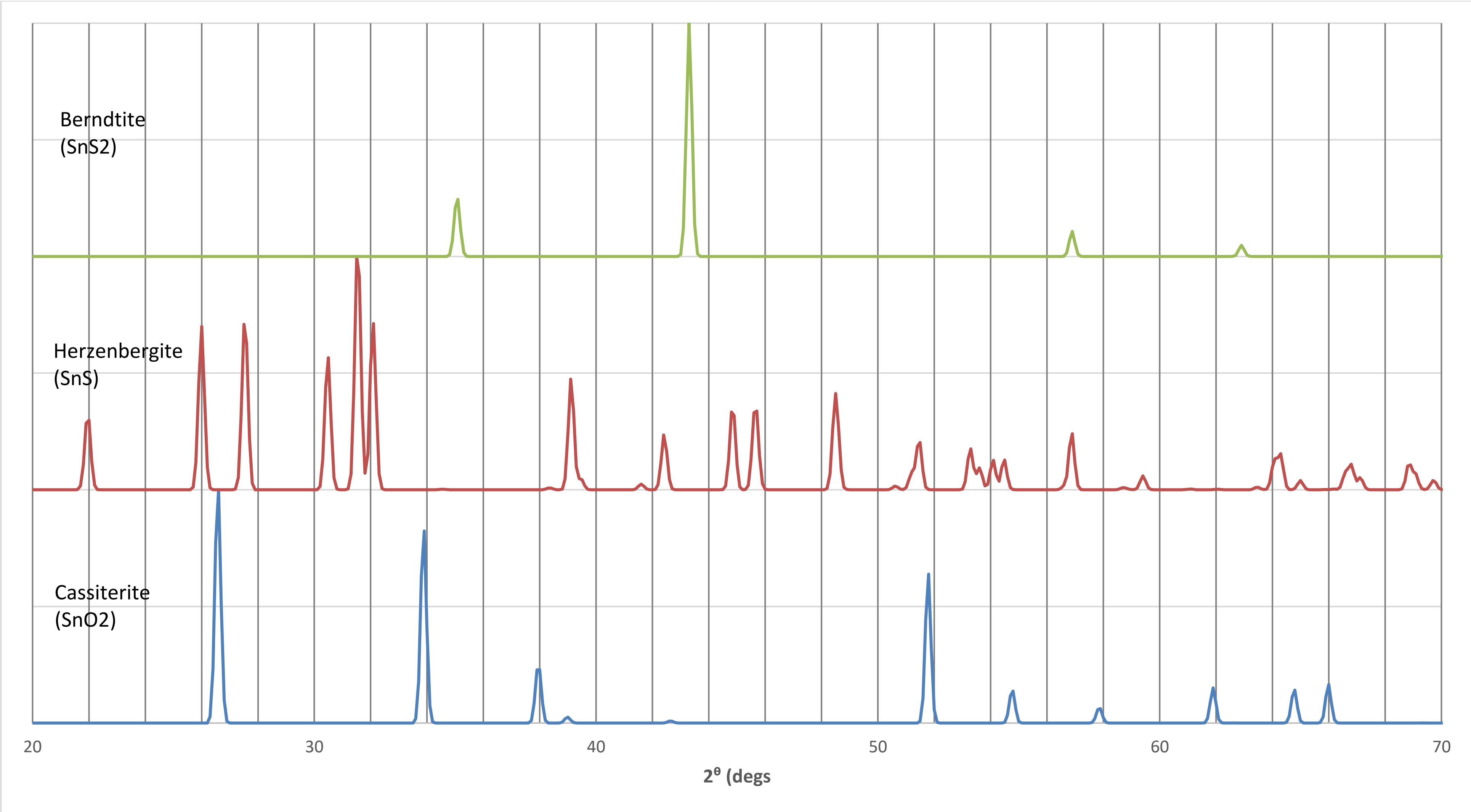


Figure 267: Common tin compounds (Aarhus University 2017).

Appendix V- Statistical Analysis

Statistical analysis was carried out on various sets of data, to identify whether there were association between two variables (e.g. condition of bullets and pH of soil). Spearman's rank correlation was selected for this study as the data consisted of two variables which could be ranked on a scale. Spearman's rank coefficient, or Spearman's rho (r), is a non-parametric measure of correlation between two ranked variables, making no assumptions on the distribution of data (Field 2009, 181). It is a *bivariate* method where the correlation between two variables is assessed. Gerwin and Baumhauer also utilised Spearman's to calculate relationships between soil properties and the degree of corrosion of archaeological iron finds (Gerwin and Baumhauer 2000, 70).

The symbol for coefficients is r(s), and takes value from -1 to +1. A value of +1 indicates a perfect correlation, a value of 0 implies no correlation, and a value of -1 shows a perfect negative correlation (Fletcher and Lock 1991, 105).
Spearman's rank was run through SPSS statistics software (version 22) which gives the correlation coefficient between the two variables (e.g. .583) and the significance of that value (e.g. .001). If the significance value is below 0.05 then the correlation is deemed significant (Field 2009, 181).

If there are no ties in the ranking of data, the following equation is applied for Spearman's rank:

$$\mathrm{rs} = 1 - \frac{6\Sigma d^2}{\mathrm{n}(\mathrm{n}^2 - 1)}$$

n= number of ranks
d= difference between ranks of x and y variables

However, the equation for correlation coefficient is adjusted when there are ties in the ranking, which is likely, and is applicable in the case of this study where multiple bullets score the same condition.

Example:

Two sets of data (Age and IQ) were ranked from 1-10 (table 98). In this example there are no ties in the ranks and the correlation coefficient is 0.661 (table 99). However, when ties in the ranking are added to the data (table 100), the correlation is weaker (table 101).

When there are a lot of ties in the ranked data resulting in a high *n* number, as in this study, the significance of the correlation coefficient is reduced, but is more reliable. It should be noted that if large sample sizes are used, the correlation coefficient is likely to be lower, but this does not mean that it is not statistically significant.

Age	IQ	rank x	rank y	d	d2
18	100	10	8	2	4
19	85	9	10	-1	1
20	135	8	4	4	16
21	120	7	5	2	4
22	110	6	6	0	0
23	105	5	7	-2	4
24	90	4	9	-5	25
25	150	3	2	1	1
26	140	2	3	-1	1
27	160	1	1	0	0
		10			56

Table 98: Ranked set of example data.

			Age	IQ
Spearman's rho	Age	Correlation Coefficient	1.000	.661*
		Sig. (2-tailed)	.	.038
		N	10	10
	IQ	Correlation Coefficient	.661*	1.000
		Sig. (2-tailed)	.038	.
		N	10	10

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

Table 99: Example of Spearman's rank from SPSS, showing a coefficient of 0.661 which is significant to 0.38 at the 0.05 level.

Age	IQ	rank x	rank y	d	d2
18	100	10	8	2	4
19	85	9	10	-1	1
20	135	8	4	4	16
21	110	7	6	1	1
22	110	6	6	0	0
22	105	6	7	-1	1
24	90	4	9	-5	25
25	150	3	2	1	1
26	140	2	3	-1	1
26	100	2	8	-6	36
		10			86

Table 100: Ranked set of example data with repeats of data in age and IQ.

			Age2	IQ2
Spearman's rho	Age2	Correlation Coefficient	1.000	.356
		Sig. (2-tailed)	.	.313
		N	10	10
	IQ2	Correlation Coefficient	.356	1.000
		Sig. (2-tailed)	.313	.
		N	10	10

Table 101: Example of Spearman's rank from SPSS using ranked data including ties. SPSS has adjusted the equation to make allowances for the ties in ranks and the new correlation coefficient is 0.356.