GAUGING PRESERVATION

THE EFFECTS OF OXIDISING CONDITIONS IN SOILS ON THE PRESERVATION OF ARCHAEOLOGICAL MATERIAL DATA

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– DECLARATION –

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration, except as specified in the text and acknowledgements. No portion of this work has been, or is being, submitted for any other degree or qualification. This dissertation does not exceed 80 000 words.

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– ABSTRACT –

Preservation and conservation of archaeological sites is an important and everyday issue for archaeologists in Britain and around the world. Whether the site is waterlogged or dry, exposed or buried, in need of rescue or *in situ* preservation, issues concerning the quality of preservation of organic material in particular, are at the forefront of many past and current research endeavours. In completely waterlogged, anaerobic environments, we would expect excellent preservation as the lack of oxygen limits biological activity. Likewise, in a highly aerobic but completely dry environment, we would expect excellent preservation as lack of water for biological activity would limit the deterioration of organic remains. Environments that exist outside these ideals have been largely ignored due to the complexity of the preservation environment. While there have been attempts to investigate the effects of oxidation on the preservation of different types of artefacts themselves, the effects of oxidation on the soils and how these changes can affect the preservation environment, with specific reference to an identifiable soil characteristic, have not been explored. By examining the changes these soils go through under different oxidising environments, it is possible to identify the level of preservation of organic material that can be expected on an archaeological site.

Iron oxide can be used as an indicator of oxidation as it is very sensitive to changes in levels of oxygen within the buried environment. By examining the different types of iron oxide deposition in the soils, it is possible to identify the type of hydrological environment for that site, and hence the level of preservation that can be expected for organic archaeological material. The development of a comparative database (CDB) based on the relative deposition of iron oxide in soils, and how this relates to variations in oxidising conditions, provides a platform for identifying differing hydrological environments within archaeological sites.

The CDB is developed by using bulk and soil micromorphological analyses on non-archaeological sites, representing four major soil/geology types and environments. Oxidation experiments were carried out on these samples to assess the variation between differing rates of oxidation and seasonality influences. Once constructed, the CDB was tested using samples taken from archaeological sites of similar soil/geology type, and includes sites ranging from the Mesolithic to the Romano-British period. Archaeological samples were collected from various features and buried soils from five sites: the Late Bronze Age enclosure at Over, the Iron Age ringwork at Wandlebury, the Iron Age enclosures at Sutton Common, the Romano-British site at Marcham-Frilford and the Bronze Age field systems at Shovel Down. The results of this project indicate that the deposition of iron oxide, as identified through soil micromorphological analysis, has great potential as a tool for gauging preservation of organic material in archaeological sites throughout Britain. The use of the CDB to improve the understanding of preservation and conservation issues in Britain, and beyond, will be an essential element to any future research in this field.

This work will form an important part of all archaeological curators' repertoires for assessing preservation conditions on a site, and therefore, a gauge of the appropriate level of archaeological importance and response.

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– 1 –

INTRODUCTION TO GAUGING PRESERVATION

The preservation and conservation of archaeological sites in Britain is at the forefront of current debate by archaeologists. The key issues focus on considerations of *in situ* preservation of nationally and internationally important archaeological sites versus recording through excavation. While the preference is to preserve archaeological sites *in situ*, there will always be sites where excavation is a better solution. However, making the decision to preserve *in situ* or excavate can be complicated by poor knowledge of the burial environment and the post-depositional processes that occur within. By first identifying the soil/geology type of the site, in addition to the hydrological/oxidation environment, inferences can be made about the preservation potential for the organic material data contained within the archaeological deposits. As the introduction of oxygen into a buried environment plays a key role in decomposition of such fragile organic remains, a sensitive indicator of oxidation needs to be identified within the buried environment, which can, in turn, be used as a tool for gauging the organic preservation potential of the site.

The aims of this research are threefold. The first is to identify and characterise the range of features expressed by iron oxides as a sensitive indicator of oxidation in soils and sediments, the second is to develop a comparative database (CDB) through oxidation experiments on soils of different soil/geology types within Britain, and the third is to test this database using archaeological sites of similar soil/geology types to the CDB, in terms of the organic material preserved in relation to the patterns of iron oxide deposition. These aims permit assumptions that oxygen is the dominant factor in the decomposition of organic material, that the patterns of iron oxide deposition in soils/sediments are directly related to the hydrological/oxidation conditions present in the buried environment, and that the identification of hydrological/oxidation conditions can be used to gauge the preservation of organic material in archaeological sites of specific soil/geology types.

The abovementioned assumptions are attributable to information gleaned from the literature and are outlined in chapter two. In addition, site formation and post-depositional processes are discussed in relation to preservation. Further, different preservation conditions including waterlogged and arid buried environments, which are ideal for the preservation of organic material in archaeological sites around the world, are discussed. Current experiments for long-term preservation conditions and the effects of post-depositional processes on artefacts within the buried environment are reviewed, highlighting research areas that need to be addressed further. In order to assess the effectiveness of iron oxide distribution as a sensitive indicator of oxidation, the processes of iron oxide in the soil environment are discussed, along with an explanation of how the different patterns of iron oxide deposition can be used to identify unique hydrological/oxidation conditions that occur in the soil/sediment. Iron oxide deposition in relation to the preservation of organic material in archaeological sites is then discussed with particular reference to iron pans, their genesis and their preservation attributes. As with all research projects, it is not possible to cover all angles and with preservation of organic material in archaeological sites being such a complex issue, the parameters and limitations of this research project are outlined. Finally, the background to each of the CDB experimental sites is presented, and the reasons for the selection of each site are discussed.

Chapter three outlines the sampling strategy, laboratory experiments and analyses for the CDB. Both micromorphology and bulk samples for bulk analyses were collected from each of the CDB sites, and oxidation experiments were carried out in the laboratory to assess the effects of different rates of oxidation on the soils. Slow oxidation, representing a fluctuating groundwater table, was replicated by air drying the samples over three months, while rapid oxidation, representing the mechanical lowering of the groundwater table via pumping, was replicated by oven drying the samples at 40ºC for three days. Control samples were also collected, which were not subjected to oxidation so as to represent the in-field conditions as closely as possible. Samples were collected on a seasonal basis over a twelve month period and meteorological data used in this research was collected by MORECS and Forestry Services. The data were then run through a series of statistical analyses resulting in the development of the CDB.

The results of the bulk and micromorphological analyses for the CDB sites are presented and discussed on a site-by-site basis in chapter four. Four different soil/geology types and environments are investigated, including an alluvial brown earth under arable cultivation, a typical rendzina in a pastoral landscape, an argillic pelosol under an Oak forest, and a brown

podzolic soil under a Scots Pine forest. The results from the bulk analyses provided quantitative information about each site and the processes occurring within the soil environment, including leaching and bioturbation. However, the most informative data regarding iron oxide deposition was obtained from the soil micromorphological analyses. There was a distinct difference in the pattern of iron oxide deposition between the air dried samples and oven dried samples, which are a direct reflection on the oxidation conditions experienced by the samples. From this data, it is possible to suggest the preservation potential of each of the four soil/geology types and environments used to form the CDB.

In order to test the effectiveness of the CDB, five archaeological sites on similar soil/geology types to the CDB sites were sampled and analysed using the same bulk and micromorphological analyses used for the CDB sites. Samples were collected from archaeological features associated with iron oxide deposition as identified in the field. The results are presented and discussed on a site-by-site basis, with particular reference to the relationship between iron oxide and organic preservation for each site. The patterns of iron oxide deposition reflect the current hydrological/oxidation environment present at each of the sites. The information gleaned from the micromorphological and bulk analyses provides context and quantification for the post-depositional processes occurring within the buried environment of the four different soil/geology types. However, using iron oxide as an indicator of oxidation proves more effective for archaeological deposits that are influenced by groundwater fluctuations than those that are not.

Chapter six brings together the data from the CDB and the archaeology sites and discusses the effectiveness of using iron oxide deposition patterns as a sensitive tool for gauging preservation of organic material in archaeological deposits. The practical application of the CDB for gauging preservation is outlined, with suggested improvements for speed and accuracy incorporated into the discussion. In addition, issues of preservation and conservation are discussed in line with Planning Policy Guidance 16 (DoE 1990), which stresses the preference of *in situ* preservation of an archaeological resource over recording through excavation. Further, the application of the CDB to ascertain the existing hydrological/oxidation environment present in archaeological sites, which are discovered during planning and development schemes, is discussed, as well as the potential of the CDB being used as a tool for continued monitoring of sites that are preserved *in situ*. The application of the CDB to gauge the preservation potential of organic archaeological remains

is argued to be an effective curatorial tool for archaeologists in Britain, especially in sites that are influenced by groundwater fluctuations.

Finally, chapter seven summarises the main aims and results of the research project, discusses the successes and limitations of the CDB, and proposes future channels of research, which aim to improve the accuracy and scope of the CDB as a sensitive tool for gauging the preservation potential of organic material in archaeological sites within Britain. In addition, future adaptations are suggested, which will enable the global applicability of the CDB for a wider variety of soil/geology types and environments.

– 2 –

PROCESSES OF PRESERVATION AND OXIDATION IN THE BURIED ENVIRONMENT

2.1 INTRODUCTION

Preservation and conservation of archaeological sites continues to be an important issue for archaeologists in Britain. Whether the site is waterlogged or dry, exposed or buried, in need of recording through excavation, or *in situ* preservation, issues concerning the quality of preservation of organic material in particular, are at the forefront of many past and current research endeavours. In particular, in these days of cost conscious, development funded archaeology, a quick and easy way of gauging preservation environments on site is essential for gauging the level of curatorial input to the planning process concerning the future of the site. For example, if a site is well-preserved and deemed nationally or internationally significant, the *in situ* preservation of the site is preferred, and the developer may be encouraged to alter their original development plans (see DoE 1990). In order to understand the preservation of organic material in archaeological sites, it is first important to identify the critical elements that are responsible for the preservation and/or deterioration of this material within the buried environment.

In this chapter, I first discuss site formation and the roles of anthropogenic activity and natural processes. Second, I outline basic concepts involved in the preservation/deterioration of inorganic, and on a more detailed level, organic material in archaeological sites, and how variations in the conditions of the buried environment can affect the preservation of archaeological material data. Third, current research in preservation and conservation of organic material in archaeological sites is discussed, along with current experimental research into post-depositional processes and its effect on the preservation/deterioration of organic material. Fourth, the role of oxidation and iron oxide in the preservation/deterioration process

of organic material is outlined. Further, iron oxide as an indicator of oxidation, and how it can be used to predict the current hydrological environment within the soil, is discussed. Fifth, the limitations of this research are outlined, indicating the parameters used in this study and why these parameters were chosen. Finally, the background and suitability of each site selected for the compilation of the comparative database is explored.

2.2 SITE FORMATION: NATURAL AND ANTHROPOGENIC PROCESSES

Site formation processes involve two main factors: the first, anthropogenic, where objects associated with human behaviour are deposited within the natural sphere, and second, the natural, where processes such as erosion, weathering and bioturbation take place in altering the original deposition pattern of a deposited object (Butzer 1982; Evans and O'Connor 1999; Waters 1992). Natural and anthropogenic processes are entwined in the formation of archaeological sites and the preservation of their material data (Cronyn 1990; Evans and O'Connor 1999; Raiswell 2001; Rapp and Hill 1998; Ward and Larcombe 2002). Natural processes include physical, chemical and biological agents, and each plays an important role in the preservation environment of archaeological organic material data (Cronyn 2001; Raiswell 2001; Ward and Larcombe 2002).

2.2.1 Natural Processes

Physical processes, such as aggradation and erosion, can work to the benefit and detriment of archaeological site preservation (Brown 1997; Waters 1992). Aggradation can preserve archaeological material by rapid burial, thereby protecting the site from deterioration, whereas erosion can expose an archaeological site where its fragility becomes immediately apparent (*ibid*). Aggradation and erosion can also affect the context of archaeological sites; colluvial events can move a site down a hillslope, while erosional events can transport material from its original context to a secondary depositional context (*ibid*). These issues are further explored in a copious body of literature and will not be discussed in detail here (Bell and Boardman 1992; Bell and Walker 1992; Brown 1997; French 2003; Gerrard 1992; Goudie 1990; Rapp and Hill 1998; Waters 1992). The natural fluctuation of groundwater levels is a physical process that plays an important role in the preservation of archaeological organic material (Rose 2004; Welch and Thomas 1998). The rise in groundwater levels above the level of archaeological depositional environments provides an anaerobic environment ideal for the preservation of organic material (Van de Noort and Davies 1993; Welch and Thomas 1998).

The term anaerobic (or anoxic) is used to describe an environment which is devoid of free oxygen, whether by inundation of water, or by compaction of the soil or sediment (Balaam *et al.* 1982; Chapman and Cheetham 2002; Gebhardt and Langohr 1999). As will be discussed in detail below, lack of oxygen prevents the decay of organic material by the cessation of biological processes (Caple and Dungworth 1997; Cronyn 2001; Van de Noort and Davies 1993). Above the level of the groundwater table is an aerobic (or oxic) environment, which is an environment rich in oxygen that can have detrimental effects on the preservation of organic material, as it promotes biological processes (Caple and Dungworth 1997; Cronyn 2001; Gebhardt and Langohr 1999; Van de Noort and Davies 1993). Between the anaerobic and aerobic zones is the fluctuating zone, where natural rises and falls of the groundwater table result in a cycle of reducing and oxidising conditions, known as redox processes (Breuning-Madsen and Holst 1998; Courty *et al.* 1989; Gerrard 1992). It is in this zone where chemical and biological processes can have the greatest effect on preservation conditions.

Chemical processes, such as changes in acidity and alkalinity levels, and weathering through chemical dissolution, may have adverse effects on the preservation of organic material; although in some cases chemical processes can promote a good preservation environment (Cronyn 1990). Generally, alkaline environments preserve material such as bone, molluscs, and other carbonised material; however, with the addition of anaerobic conditions, the range of organic material preserved in these conditions greatly increases, such as non-carbonised plant material and other textiles (Cronyn 1990; Evans and O'Connor 1999; French 2003). Acidic environments generally encourage the preservation of pollen and plant remains and are detrimental to all other organic material, except where anaerobic conditions are present (*ibid*). The acidity or alkalinity of an environment does not always remain stable and often results in localised patches of increased acidity or alkalinity (Caple and Dungworth 1997; Raiswell 2001; Van de Noort and Davies 1993). These variations occur as a result of numerous factors including physical, chemical and biological processes. For example, a colluvial event can cause compaction of soil pore space inhibiting oxygen, which, in turn, causes the cessation of biological activity, which prevents the total decomposition of organic material, and the release of acids from this material can cause an acidic micro-environment (Cronyn 1990, 19). Conversely, an alkaline micro-environment can form in an otherwise acidic environment where an upward movement of water from the groundwater table, and its subsequent evaporation at the surface, can result in the deposition of soluble salts, causing a decrease in acidity (Raiswell 2001, 603; Van de Noort and Davies 1993, 111). An adjunct to this is where chemical processes can promote preservation of organic material. For example, the corrosion

of a metal object, such as a copper belt buckle, in an aerobic environment provides a micro-environment which is toxic to micro-organisms (Cronyn 1990, 28). This micro-environment protects the associated textiles from decay by way of biological processes (*ibid*).

Biological processes such as bioturbation and microbial activity are paramount to the destruction of archaeological organic material. Bioturbation is the disturbance of sediment and/or soil by fauna and flora, varying in scale from mites and earthworms, roots and decay, to moles and rabbits, and tree throw (Limbrey 1975; Rapp and Hill 1998; Waters 1992). It results in the destruction of organic material and destroys stratigraphic context (*ibid*). The implications of bioturbation on the archaeological and palaeoenvironmental record are well documented, and therefore, will not be explored in detail here (*ibid*). The pivotal issue for this research project is the effect of micro-organisms on the preservation/destruction of organic material in archaeological sites (Ambrose 1970; Caple and Dungworth 1997; Cronyn 2001; Limbrey 1975; Van de Noort and Davies 1993). There are two main types of micro-organisms: aerobic, which only survive in zones rich in free oxygen, and anaerobic, which can survive in zones where free oxygen is lacking (*ibid*). Aerobic micro-organisms, due to their copious presence, cause the most damage to organic material, and in highly aerated environments can result in the total destruction of organic material in archaeological sites (*ibid*). Anaerobic micro-organisms exist, for example, in waterlogged sites and are not directly detrimental to organic material (*ibid*). Unlike aerobic micro-organisms, which require oxygen for their respiration, anaerobic micro-organisms survive by reducing inorganic chemicals such as carbon dioxide, sulphates, nitrates, manganese and iron (Cronyn 1990, 17). This inefficient form of respiration causes the excretion of organic acids, which can effect changes in the pH of the surrounding environment (*ibid*).

2.2.2 Anthropogenic Processes

Past and present human activities and their effects on the environment are well studied by numerous authors (Bell and Walker 1992; Butzer 1982; Goudie 2006; Mannion 1991; Roberts 1998; Simmons 1996; Van de Noort and Davies 1993), and such activities can have both positive and negative effects on the preservation of organic material in archaeological sites. To begin with, past anthropogenic activities are responsible for the creation of the archaeological record. Even prior to deposition, anthropogenic activity can affect the chances of preservation of organic material. For example, through the cooking of seeds and grains the charred remains have a much greater chance of survival in the archaeological record than

uncharred remains, as carbon is toxic to most micro-organisms (Cronyn 1990, 2001; Evans and O'Connor 1999). The anthropogenic processes that will be discussed here, however, will focus on post-depositional activities that affect or alter the preservation environment of archaeological sites. Comparable to natural processes, anthropogenic processes are divided here into three main areas: physical, chemical and biological.

Physical processes include activities such as land clearance and irrigation for agriculture and pastoralism, which occur in the past and present and also have implications for anthropogenically induced biological processes, to which I shall return later. Activities that are perhaps more prevalent today than in the past, such as water abstraction/quarrying, large scale irrigation and dam building, also affect the preservation of organic material in archaeological sites (Caple and Dungworth 1997; Dunn *et al.* 2003; French 2003; Goudie 2006; Holden *et al.* 2006; van Heeringen *et al.* 2004). Water abstraction is the mechanical, and often rapid, lowering of the natural groundwater table by pumping the water from one area into another in order to access materials for mining, such as gravels and clays (Bidwell 2005; French 2003, 12; Holden *et al.* 2006; Jyr-Ching Hu *et al.* 2006; Kamra *et al.* 2002; Mkwizu 2003; Procter *et al.* 2006; Shepherd *et al.* 2006). This results in the rapid introduction of oxygen into an anaerobic environment in two ways. First, the lowering of the groundwater table exposes the anaerobic sediments and organic material to oxygen, thereby exposing any organic material to microbial attack and immediate desiccation (Caple and Dungworth 1997; Chapman and Cheetham 2002; French *et al.* 1999; French and Taylor 1985; French 2004; French and Heathcote 2003; Holden *et al.* 2006). Second, by pumping the water out of one area and into another area, oxygenated water can be introduced to a previously anaerobic environment (Bidwell 2005; Caple and Dungworth 1997, 237; French *et al.* 1999; French 2004; Holden *et al.* 2006; Jyr-Ching Hu *et al.* 2006; Kamra *et al.* 2002; Mkwizu 2003; Procter *et al.* 2006). Similarly, large scale irrigation causes dramatic lowering of the groundwater table, exposing any archaeological organic material to oxygen and eventual decay (Caple and Dungworth 1997). Dam building effects changes in soil chemistry (e.g. salinisation) and groundwater levels (Goudie 2006, 123). The flooding of a geographical area can help preserve any remains as it has been shown that anaerobic conditions can form within days of waterlogging (Breuning-Madsen *et al.* 2003; Goudie 2006). The reduction of water levels downstream from the dam can have similar effects to organic preservation as water abstraction, whereby oxygen is suddenly introduced to existing anaerobic conditions, exposing organic material to agents of destruction (Goudie 2006).

Chemical processes that occur as a result of anthropogenic activities, such as liming and fertilising fields, can affect organic preservation by altering the pH of a preservation environment (Pollard *et al.* 2004). Further, excessive agricultural and pastoral activity can cause nutrient deficiency in the soil, resulting in a once fertile environment being leached of essential soil nutrients and becoming a highly acidic environment dominated by heather and peat development (Goudie 2006, 103). However, heath and peat development is also dependant on groundwater level and geology/soil type, and acidic soils can support other forms of vegetation, e.g. Conifers (Eyre 1968; Gobat *et al.* 2004; Jenkinson 1981). The process of liming the fields is in reaction to excessive agricultural activity and is used to increase the alkalinity of the soil to improve its quality (Butzer 1982, 146). The impact of this action on the preservation of organic material can be potentially destructive. For example, pollen and some plant remains are best preserved in more acidic environments and the survival of this data becomes critical when measures are taken to alter the pH of the buried environment (Evans and O'Connor 1999; French 2003). Likewise, the preservation of material such as bone, molluscs and carbonised remains are optimal in more alkaline environments (*ibid*). However, the introduction of fertilisers can have detrimental effects on their preservation as an alkaline environment becomes more acidic (Goudie 2006, 109; Holden *et al.* 2006). The excess use of fertilisers can also cause the breakdown of soil quality and the repellence of water, leading to erosion and significant changes in soil chemistry, all of which have resounding impacts on the preservation of organic material in archaeological sites (*ibid*). Further, agricultural activities can have repercussions for the biological processes in the buried environment.

Biological repercussions of anthropogenic activity can result in significant changes to the ecosystem through land clearance and the introduction of new plant and animal species (Bell and Walker 1992, 169). Land clearance for agriculture and pasture can be detrimental to archaeological sites in the first instance by overgrazing, resulting in soil erosion and loss of archaeological material data (Ayala and French 2005; Carpenter *et al.* 2001; Cooke 1981; Evans 1997; Holden *et al.* 2006; Oztas *et al.* 2003; Strunk 2003; Valentin *et al.* 2005; Zucca *et al.* 2006); and second, total context destruction through ploughing by modern machinery (Bohn *et al.* 2001; Dexter 1997; French 2003; Holden *et al.* 2006; Saville 1990). Further, this activity often increases the aeration of the soil/sediment, allowing oxygen and micro-organisms to penetrate at greater depths down the soil profile (*ibid*). The introduction of new species can equally cause destruction of organic material in archaeological sites. For example, the introduction of a new plant species that requires greater quantities of water will

rely on deep penetration of its roots in search of water, thereby disturbing any archaeological material present and allowing pathways for microbial activity (Limbrey 1975, 286). Likewise, the introduction of new faunal species can have detrimental effects on archaeological preservation. For example, in Australia, the introduction of the rabbit and wild pig has had devastating results from burrowing and rooting, often destroying all archaeological contexts and causing an increase in soil/sediment aeration (personal observation). Finally, the ultimate biological process of archaeological destruction: people. Although it will not be discussed here in detail, it is worth mentioning the issue of current and direct anthropogenic destruction of archaeological sites through deliberate vandalism, war and development (Brodie and Walker Tubb 2002; Ford 1972; Stone *et al.* 2001). The media (McCarthy and Kennedy 2004; Whitehouse 2003), archaeological groups (e.g. World Archaeological Congress), and individual archaeologists have, at one stage or another, highlighted these problems and have lobbied for action to be taken to improve the awareness for the need of preservation and conservation of all archaeological material data.

2.3 PRESERVATION OF ARCHAEOLOGICAL INORGANIC MATERIAL DATA

Although this research project focuses on organic archaeological material data, it is important to discuss briefly the effects of reducing-oxidising conditions (i.e. cycles of aerobic and anaerobic conditions, usually associated with fluctuating groundwater tables; see section 2.6) on inorganic archaeological material, such as metals, and biominerals, such as bones and shells. The effect of these conditions on such inorganic material is well documented (Edwards 1996; Fell and Williams 2004; Kars *et al.* 2004; Keresztes *et al.* 2001; Madsen *et al.* 2004; Millard 1996; Wiedemann 1972; Wilson and Pollard 2004) and the field of research in this area continues to expand (see Kars 1998, 141).

If metal objects, such as iron, copper and lead, are buried in stable anaerobic soil/sediment environments, then a chemical reaction between the metal and the surrounding soil-water causes soluble ions to oxidise which, in turn, forms a protective layer around the object, known as a patina (Edwards 1996). It is only when the stability of the burial environment changes that this protective barrier is altered, resulting in further, destructive, corrosion of the object (*ibid*). For most metal objects, it is the oxidation of the metals, in conjunction with a moist environment, that causes the process of corrosion, be they iron, copper or lead (*ibid*). For example, a metal object made from iron (generally, an alloy of iron and carbon) can be very easily corroded, especially in the presence of oxygen and moisture; two of the key

elements in redox processes (see section 2.6 and Sease 1987, 78). The most familiar and easily identifiable corrosion product, as a result of redox processes, is rust (*ibid*). This causes the iron object to deform and often causes deep cracks and fissures in the object, which ultimately destroy the stability of the object's structure (*ibid*).

Biominerals, such as bones and shell, are also affected by changes in their burial environment, as mentioned in the previous section. The processes involved in the diagenesis of bone in the burial environment are extremely complex, and at this stage, are still not completely understood (Millard 1996) but have been investigated by many researchers (Grupe 1995; Kars 1998; Kars *et al.* 2004; Millard 1996; Nicholson 1998; Nielsen-Marsh and Hedges 2000a, 2000b; Wilson and Pollard 2004). Initial attack in an aerobic burial environment is from micro-organisms, which need oxygen to subsist (see section 2.4 for more detail) and it is less likely that such attack will take place in anaerobic burial conditions (Millard 1996, 96). The most susceptible part of the bone to be degraded under microbial activity is collagen, and this can occur within days (*ibid*). Once the collagen is removed from the bone, it becomes physically weaker (Turner-Walker and Parry 1995) and is susceptible to other chemical reactions, which can cause the degradation of the remaining mineral component of the bone, especially when cycles of reducing and oxidising conditions persist (Millard 1996, 99). In calcareous environments, total replacement of the bone by calcite can occur, and in reducing conditions, vivianite and pyrite (iron-based minerals) can form on the surface and in the walls of the bone (*ibid*, 98). However, the mechanism for this process is still not understood (*ibid*). In addition, when an anaerobic environment becomes oxidised, for example, through the dewatering of a waterlogged site, the soluble ions present (e.g. iron) oxidise, and the physical expansion of this process causes the bone to crack, leading to its eventual destruction (*ibid*, 99). Continual cycles of reducing and oxidising conditions accelerate this process of degradation (*ibid*).

2.4 PRESERVATION OF ARCHAEOLOGICAL ORGANIC MATERIAL DATA

Four main factors which affect the preservation of organic material within the buried environment are oxygen, pH, moisture and temperature. Each of these factors interacts to form either an ideal preservation environment or a potentially destructive environment for organic material. The activity of organisms is integral to the destruction of organic material in the buried environment. Organisms are pH sensitive, require some degree of water, and will not generally tolerate extreme temperatures (Cronyn 1990, 15). Most organisms also require

oxygen, although some micro-organisms can survive in anaerobic conditions (Cronyn 1990, 15).

Wetland or waterlogged environments are generally ideal for preservation, although the type of organic material preserved depends on pH. If a site is waterlogged and therefore anaerobic, the potential of micro-organisms surviving to destroy the organic material without oxygen is very low. Further, if the pH of the environment is highly acidic, those micro-organisms that do survive in anaerobic conditions are often restricted by acidity and temperature extremes. In anaerobic acidic environments, most organic material is excellently preserved with the exception of biominerals, such as bone and molluscs, which preserve well in anaerobic alkaline environments. There is a vast body of literature concerning the preservation of archaeological organic material in wetland environments throughout northern Europe (Caple and Dungworth 1997; Coles 1995; Coles *et al.* 1999; Cox *et al.* 1995; Kenward and Hall 2000; Purdy 2001; Raftery 1992; Raftery and Hickey 2001). Examples include the preservation of bog bodies, such as Lindow Man in Britain (Turner 1999), and the Tollund Man and Elling Woman in Denmark (Fischer 1999). In addition, the preservation of prehistoric wooden trackways in Europe is also well documented, including the Neolithic Sweet Track (Brunning 1999), the trackways in the Derryville Bog in Ireland (Casparie 2001), and a collection of trackways in the Norwegian bogs (Smedstad 2001). Other archaeological sites that are currently undergoing conservation and monitoring are Flag Fen in Peterborough (Pryor *et al.* 1992) and Sutton Common in South Yorkshire (Parker Pearson and Sydes 1995; 1997) (also see appendix A, table A-1).

At the other end of the spectrum are dryland environments, of which arid and semi-arid environments generally provide good preservation conditions for most organic remains. The lack of moisture in arid environments prevents most micro-organisms from surviving, and those micro-organisms that are present in arid conditions only feed on fresh organic material (Fairbridge and Finkl 1979, 470; Hansen 2001; Laudermilk and Munz 1938; Wells 1977; Wilkinson and Stevens 2003, 163). Therefore, once the organic material is buried, it is generally safe from destruction (Hansen 2001; Laudermilk and Munz 1938; Wells 1977; Wilkinson and Stevens 2003, 163). The process of desiccation preserves organic material, such as plant material, and in some cases, textiles, hair and skin, as well as biominerals, such as bones and shells. Examples of preservation by desiccation include naturally mummified human remains in Northern Chile (Aufderheide *et al.* 2005; Holden and Núñez 1993) and China (Lin *et al.* 1995), and fossilised bone in Nubia (Race *et al.* 2005). The preservation of

archaeobotanical and faunal remains are common in North America (Davis 1990; Diamond 2001), Mexico (Byers 1967), Egypt (van der Veen 1996), Zaire (Sept 1994), Spain (Carrión 1995), and occasionally elsewhere in the Mediterranean (Hansen 2001).

Excellent preservation in wetland and dryland environments have resulted in a multitude of research projects, and the contributions to understanding preservation environments in these areas is unremitting (Banwart 1996; Caple and Dungworth 1997; Chapman and Cheetham 2002; Corfield *et al.* 1996; Davis 1990; French and Taylor 1985; French 2004; Holden *et al.* 2006; Hopkins 1996; Kenward and Hall 2000; Pollard 1996; Teague 1999; Van de Noort *et al.* 2001; Van de Noort and Davies 1993; van der Veen 1996; Ward and Larcombe 2002; Welch and Thomas 1998). However, our knowledge and understanding of what goes on in environments that exist outside such ideal preservation conditions remain somewhat ambiguous. While it is assumed that this intermediate preservation zone is generally detrimental to the preservation of organic material, research into developing a gauge for the degree of preservation, based on identifiable soil characteristics, has not been attempted due to the complexities involved with the preservation environment, such as different soil/geology types and existing hydrological/oxidation conditions within the buried environment. This research project uses data from oxidation experiments on soils of differing soil/geology types and environments to assess the effects of oxidation on organic material. An identifiable soil/sediment characteristic, iron oxide, is used as a gauge for preservation, as iron is sensitive to changes in oxidation levels within soils (see below). The data from these experiments form a comparative database (CDB), which is used as a predictive tool for identifying the preservation of organic material in archaeological sites within Britain. One key project involved in long-term experiments that investigate preservation conditions of organic and inorganic archaeological material data in a buried environment, is the Experimental Earthwork Project, initiated by the British Association for the Advancement of Science in 1958 (Bell *et al.* 1996).

2.5 THE EXPERIMENTAL EARTHWORK PROJECT – A REVIEW

The Experimental Earthwork Project was developed from the realisation "that monuments are continually being modified by nature and that evidence of weathering, denudation and silting can be as informative as the artefacts sometimes found in them" (Ashbee and Cornwall 1961, 129). Bank and ditch systems based on, though not replicating, those commonly found throughout Britain were constructed on two sites: Overton Down, Wiltshire (constructed in

1960), which is a humic rendzina on chalk downland; and Morden Bog, Wareham (constructed in 1963), which is an acidic lowland podzol (Crowther *et al.* 1996; Jewell 1993; Macphail *et al.* 2003). The bank and ditch systems were designed for excavation and rigorous scientific investigation over time intervals of 0.5, 1, 2, 4, 8, 16, 32, 64 and 128 years (Bell *et al.* 1996; Jewell 1993). An array of organic and inorganic material was placed within and beneath the earthworks to assess the rate and nature of the degradation (Bell *et al.* 1996; Caple 2001; Jewell 1993). Such materials included a variety of textiles (cotton, wool, linen, leather, goatskin and rope), human bone (fresh, cremated and bone dust) and faunal bone (cooked and uncooked), charred and uncharred wood (oak and hazel), and *Lycopodium* spores to simulate pollen deposition; along with pottery, flint, copper and steel (Bell *et al.* 1996, 43; Lawson *et al.* 2000, 273). Biological activity within the earthworks, on their surfaces, and in the surrounding environment, was studied along with pedological changes (Bell *et al.* 1996; Crowther *et al.* 1996). Initially, external (macro-scale) changes to the earthworks were recorded at each excavation interval (i.e. vegetation changes on, and around, the earthworks, compaction of the bank, and silting of the ditch). More detailed (micro-scale) analysis of the soils from the earthworks were introduced at the 32-year excavation, where soil micromorphology and geochemistry were used to look at soil compaction and structural change, changes in soil pH, earthworm activity and bioturbation, organic matter and plant remains, and replacement of organic material by iron and iron panning (*ibid*). Off-site samples were taken as a representation of the original soil structure prior to earthwork construction (Crowther *et al.* 1996, 98; Macphail *et al.* 2003, 78).

For the purpose of my research, I will focus on the results of the sediment studies for the Experimental Earthwork Project. For more detailed discussion on other aspects of this project please see Jewell and Dimbleby (1966) and Bell *et al.* (1996). The results and discussion reviewed here pertain to the 32-year excavations.

The Overton Down bank comprises a central turf stack, overlain by topsoil and three layers of chalk rubble, deposited in the order excavated from the ditch, and the “buried materials” were placed within and beneath the turf stack and the chalk rubble during initial construction (Crowther *et al.* 1996, 97). The soil analysis from the buried soil beneath the turf stack, when compared to the control profile, revealed a significant decrease in soil pore space and consequently a decrease in biological activity from soil fauna (e.g. earthworms) (*ibid*, 103). Further, there were fewer *in situ* roots and those that were present were very poorly preserved, and “seem to occur as ‘ghost’ features comprising pale yellow parenchymatous and/or

brownish epidermal remains, or as very fine fragments within the mineral soil" (*ibid*, 105). Crowther *et al.* (1996) also noted a decrease in pH from a range of 7.5 to 6.4 in the control soil, down to 5.6 in the buried soil, indicating that decalcification and leaching were taking place. This was unexpected as the authors had assumed that "alkaline groundwater seeping through the chalk of the bank would have tended to neutralise this acidity" (*ibid*, 106). This process of acidification is attributed to microbial activity during the transition of the buried environment from aerobic conditions to more reducing or anaerobic conditions (*ibid*). There is an increase in the presence of iron and manganese nodules when compared to the control soil, as well as replacement of organic material by iron. With the combination of reduced soil pore space from compaction and the breakdown of organic material by microbial activity, the buried soil beneath the turf stack has formed an anaerobic micro-environment allowing the mobilisation of iron and manganese through cycles of reducing and oxidising conditions (*ibid*). Overall, there appears to be poorer preservation of organic material in the upper, more aerated zones of the turf stack and better preservation of organic material by way of iron replacement and 'ghost' features in the lower, more anaerobic zones (*ibid*, 108).

However, the results for the samples taken from the buried soil beneath the chalk of the bank reveal a different story. Although there was significant compaction in the buried soil when compared with the control, the soil beneath the chalk bank was more aerated than that beneath the turf stack (*ibid*). Biological (earthworm) activity was also greater in the soil beneath the chalk bank than the turf stack, most likely causing an increase in pH to 7.9 and an increase in organic decomposition (*ibid*, 109). The aerobic conditions of the soil beneath the chalk bank has inhibited the mobilisation of iron and manganese by way of redox processes, thereby resulting in fewer nodules present than in the soil beneath the turf stack (*ibid*, 110).

Similar in construction to Overton Down, the Wareham bank consists of a central turf stack overlain by subsoil sand layers in the order they were excavated from the ditch, with the "buried materials" placed in and beneath the turf stack and sand layers prior to construction (Bell *et al.* 1996, 217; Macphail *et al.* 2003, 78). Compaction and reduction of soil pore space is more significant in the soils beneath the turf stack than the soils beneath the sand layers, resulting in a more aerobic environment in the latter (Macphail *et al.* 2003, 91). This increased aeration in the soils beneath the sand layers has resulted in an increase in biological activity (earthworms) contributing to the decomposition of organic material (*ibid*). The soil beneath the turf stack, although generally aerobic, is significantly wetter than the soil beneath the sandy layers and biological activity has been more limited in this damper environment

(*ibid*). Macphail *et al.* (2003, 87) suggest that a gleyed micro-environment is possible and that iron replacement of organic material (roots) and mite excrement present in the soils beneath the turf stack can be attributed to 'secondary' podzolisation rather than redox processes. This is a somewhat confusing conclusion as podzolisation is a long-term process and the replacement of organic material by iron oxide is more commonly attributed to repeated wetting and drying cycles (Breuning-Madsen and Holst 1992; Ralston 1979, 424).

Crowther *et al.* (1996) and Macphail *et al.* (2003) compare their findings with archaeological sites in Britain with particular emphasis on the presence of iron replacement of organic material, nodules and panning. They attribute these features to compaction, biological activity and subsequent organic decomposition, anaerobic micro-environments and podzolisation processes (Crowther *et al.* 1996; Macphail *et al.* 2003). It is on this premise that iron oxide deposition can be used as a sensitive indicator of oxidising conditions and consequently, a gauge for organic preservation in archaeological sites.

2.6 Processes of Iron Oxide in the Soil Environment

Iron is ubiquitous in the soil environment and it exists in groundwater, rocks, minerals, soils/sediments and organic material, such as roots and leaves (Cronyn 1990, 17; Loeppert and Inskeep 1996; Schwertmann and Cornell 2000, 13; Welch and Thomas 1998, 16). It is an essential source of energy for micro-organisms (Murad and Fischer 1988, 7). Iron can exist in the soil environment in both oxidised (ferric) and reduced (ferrous) states (Lindsay 1988, 37). The presence of ferrous and ferric iron in the soils relies on one key process that takes place through the reduction of oxygen in the soil, the introduction of water and/or the compaction of soil pore space, and in some cases, the activity of micro-organisms (Limbrey 1975; Lindsay 1988; Loeppert and Inskeep 1996; Ralston 1979; Stucki *et al.* 1988; van Breemen 1988). This process is known as redox and involves cycles of reducing and oxidising conditions in the soil environment (*ibid*). The deposition of iron oxide features in soils and sediments is driven by cycles of reducing and oxidising conditions (Banwart 1996; Evangelou 1998; Holden *et al.* 2006; Olivie-Lauquet *et al.* 2001; Pollard 1996). The terms reducing and oxidising, with respect to soil-water chemical processes, refers to the transference of electrons between chemical elements (e.g. Fe and Mn) where electrons are donated in oxidising conditions, and accepted in reducing conditions (*ibid*). The ability of a chemical element, such as Fe or Mn (see section 2.7 below for discussion on Mn), to undergo transformations between oxidising and reducing conditions depends on the mineral solubility (Fe and Mn can be highly soluble),

soil-water pH (acidic conditions can promote a reducing environment for Fe and Mn), mineral surface chemistry, the availability or presence of certain chemical species (e.g. Fe and Mn), the electrical conductivity of the solution, and the volatility of chemical species (the ability for the mineral to transform between soluble and solid states) (*ibid*). Redox reactions (reducing-oxidising cycles) are affected by a number of factors, including pH, temperature and microbial activity (*ibid*).

The movement and deposition of iron through the soil profile can occur as a result of three main processes: physical, chemical and biological. The physical and chemical processes involved in the movement and deposition of iron in the soil are intertwined (Limbrey 1975; Lindsay 1988; Loeppert and Inskeep 1996; Ralston 1979; Stucki *et al.* 1988; van Breemen 1988). The chemical process of the transformation of ferric iron to ferrous iron occurs as a result of either a reduction in pH to a highly acidic environment or as a result of anaerobic conditions (*ibid*). While reducing conditions exist, ferrous iron can travel in the soil solution through the capillary action of the soil or through the natural fluctuations of the groundwater table (*ibid*). When the ferrous iron reaches areas that are rich in oxygen, the ferrous iron will oxidise to form ferric iron (*ibid*). In the ferric state, iron can travel through the soil with clay through illuviation (see below) (*ibid*). In addition, the chemical weathering of the parent material as a process of soil development results in the release of iron, which may be found as pure iron nodules (or relic nodules), and can move through the soil profile in the pore space or be redistributed by bioturbation (Bullock *et al.* 1985; Limbrey 1975; Stoops 2003; Stucki *et al.* 1988).

Weathering of rocks and minerals are categorised into two main processes: disintegration, otherwise known as the physical breakdown of rocks and minerals, and decomposition where parent rocks and minerals are altered via chemical weathering (Andrade *et al.* 2002; Greenland and Hayes 1978, 10). While physical weathering is often caused by differential thermal expansion along different crystallographic axes when the rock or mineral is heated, by expansion of water in rock fissures when ice is formed or by abrasion and grinding from moving ice and rapid water movement, chemical weathering is affected by other factors (Chigira and Oyama 1999; Greenland and Hayes 1978, 10). These main environmental factors include temperature, pH, water regime, redox and biological activity (Greenland and Hayes 1978; Murad and Fischer 1988, 6). The role of water and temperature in weathering are such that the rate of weathering increases in higher temperatures and is limited in the absence of water (e.g. arid environments) (*ibid*). Redox and biological activity are closely related with

regards to oxygen availability and relative position to the groundwater table and both can promote weathering and the release of iron from minerals (*ibid*). Further, high concentrations of organic acids in soil waters can increase mineral decomposition and the subsequent release of iron (*ibid*). This iron can be reduced or complexed and is easily removed from its formation site and carried over a considerable distance (*ibid*). While the source of iron in the latter instance is from weathering of the parent material, the transport of iron in its soluble, ferrous form and its subsequent re-deposition away from the site of origin as ferric oxide is the result of redox processes in association with groundwater movement. While redox processes are fundamental to the design experiment for this project, weathering as a direct source of iron is not addressed here as none of the sites studied showed clear evidence of mineral alteration via weathering processes (see appendix F). Furthermore, chemical weathering is considered to be a major factor in more tropical and sub-tropical environments than temperate climates, such as Britain (*ibid*). Therefore, while the author acknowledges that some iron oxide pedofeatures, for example iron coatings (see below and chapter 3), can occur as a result of *in situ* weathering of minerals, there was no evidence that this process occurred in the soil samples, which were analysed using soil micromorphology (see chapter 3 and appendix F).

Finally, microbial activity is responsible for the presence of biogenic iron in the soil environment (Fortin and Langley 2005; Rowell 1981; van Breemen and Buurman 1998). The transformation of ferrous iron to ferric iron in both aerobic and anaerobic environments, with pH ranging from acidic to alkaline, can occur through the consumption of organic matter and respiration by micro-organisms (Fortin and Langley 2005, 4). One of the main drivers of redox processes is microbial activity. In oxidised conditions aerobic micro-organisms thrive due to the large quantities of oxygen available in the soil environment (Bohn *et al.* 2001; Evangelou 1998; Gobat *et al.* 2004; Goodman 1988; Greenland and Hayes 1978; Holden *et al.* 2006; Hopkins 1996; Jenkinson 1981; Olivie-Lauquet *et al.* 2001; Rowell 1981; Sparks 1995). However, when these oxidised conditions are flooded with water, for example, with a seasonally fluctuating groundwater table, the oxygen is depleted as the water in-fills the soil pore space and the anaerobic micro-organisms begin to thrive (*ibid*). These organisms first use up the remaining oxygen available in the soil water, and then use decaying organic material and other ions, such as iron and manganese, to subsist *(ibid*). As discussed above, in aerobic conditions, oxygen is used as an electron donator in order to oxidise ions such as iron and manganese, but in anaerobic environments, free oxygen is absent, and organic matter, which has localised anaerobic zones produced through photosynthesis, can be decomposed (or oxidised) by the micro-organisms present, using oxidised ions, such as iron and manganese,

as electron acceptors, resulting in complete anaerobic conditions and an increase in soluble ions (*ibid*). Once the soil becomes waterlogged, anaerobic conditions, via microbial consumption and respiration, can take up to three months (van Breemen and Buurman 1998, 65). Redox by microbial activity is certainly more prolific in aerobic environments and is responsible for much of the deterioration of organic material in archaeological sites (Holden *et al.* 2006; Hopkins 1996), as discussed above. In anaerobic environments, microbial activity is reduced to those micro-organisms that can survive in anaerobic conditions (Fortin and Langley 2005, 5). These micro-organisms gain energy by oxidising ferrous iron and, unless they are present in great numbers, have a limited effect on the degradation of organic material in archaeological sites where anaerobic conditions persist (*ibid*, 5). However, research into the production of biogenic iron by micro-organisms remains a developing field and distinguishing between abiotic (chemical) and biotic (microbial) iron is proving difficult (*ibid*, 14).

2.7 A Note on Manganese

Manganese (Mn) is an important component of the soil environment and in most cases is coupled with iron. Manganese behaves in much the same way as iron, mirroring its behaviour in physical, chemical and biological processes (Courty *et al.* 1989; Gambrell 1996; Gounot 1994; Johnson *et al.* 1995; Limbrey 1975). As with iron, manganese can also move through the soil profile either through the translocation of clay, otherwise known as eluviation/illuviation processes (Cremeens 2005), or in solution. The change from soluble Mn to oxidised Mn and vice versa can occur as a result of chemical changes from cycles of anaerobic environments to aerobic environments due to changes in groundwater levels. Alternatively, changes in soil texture may provide an impermeable barrier and create reducing conditions through the creation of a perched watertable (Courty *et al.* 1989; Gambrell 1996; Limbrey 1975; Marin and Giresse 2001). Manganese can also be processed from soluble Mn to oxidised Mn (and vice versa) through microbial respiration and consumption activities (Gounot 1994; Johnson *et al.* 1995). As manganese is so intrinsically linked with iron, a discussion of manganese and iron oxide in relation to oxidation and preservation of organic material will be presented during the course of this thesis.

2.8 Iron Oxide as an Indicator of Oxidation

Reducing and oxidising cycles are pertinent to the movement and deposition of iron oxide in soils and sediments. The process by which these redox cycles take place will have direct

effects on the type of deposition of iron oxide in the soil, which can be identified through micromorphological analysis (Courty *et al.* 1989, 179). Iron coatings (figure 2.1a) occur as a result of precipitation of iron-rich clay down profile from an eluviated horizon to an illuviated horizon (Gerrard 1992, 96; Stoops 2003). Eluviation/illuviation is a soil formation process whereby "finely dispersed humus and clay particles, as well as other weathering products, can move as colloidal suspensions from upper, **eluvial** horizons to **illuvial** horizons lower in the profile, where they are redeposited" (Bridges 1997, 35). Coatings are also related to plant respiration and concentrated activities of micro-organisms (Courty *et al.* 1989, 180). The replacement of organic material by iron occurs over repeated redox cycles as the iron becomes "trapped" in the organic material present in the soil creating pseudomorphs of the plant cells (Courty *et al.* 1989, 180; Crowther *et al.* 1996, 113; Ralston 1979, 424). A pseudomorph (figure 2.1b) occurs when iron completely replaces the organic material whilst maintaining the cell structure (Bullock *et al.* 1985). Staining (figure 2.1c) occurs in the soil when oxygen is introduced at a slow rate whereas neo-formed (or diffuse) nodules (i.e. nodules that are formed *in situ* in the soil fabric) occur when oxygen is introduced at a fast rate (figure 2.1d) (Gerrard 1992, 96; Ralston 1979, 424). The concept of different rates of oxidation resulting in variations in iron oxide deposition in soils and sediments, as identified in the literature (*ibid*), is used in this research design to highlight varying oxidation conditions, and therefore, variations in the preservation state of organic material. Generally, oxidation is rapid where there is an absence of moisture or where the oxidation demand is low (Bohn *et al.* 2001, 108). Therefore, if moisture is rapidly abstracted from the soil/sediment, oxidation will occur rapidly, resulting in an increased amount of diffuse iron nodules, as ferrous iron oxidises into ferric iron (Bohn *et al.* 2001, 108; Gerrard 1992, 96; Ralston 1979, 424). Conversely, if the rate of oxidation is slow, for example, in the case of a fluctuating groundwater table, where soil/sediment is being seasonally flooded with repeated cycles of oxidising and reducing conditions, then the oxidation of iron is going to be slow. Therefore, the slow oxidation of soil/sediment in conditions where moisture is variable and consistently present will have an effect on the pattern of iron oxide deposition and will result in iron staining (*ibid*). It should be noted here that the term 'staining', as used for this research project, is used to define iron pedofeatures at the micro-scale, i.e. using soil micromorphology. In the field, iron staining as defined here would appear as mottles in the soil/sediment profile. Likewise, iron oxide deposition as the result of oxidation along channels or roots (cf. Stoops 2003), will be localised around soil pore spaces/voids or organic material and are not to be confused with the presence of diffuse iron nodules, which are the result of

rapid oxidation, as discussed above. It is important to identify such pedofeatures in context within the soil fabric using soil micromorphological analyses (see chapter three).

Finally, numerous neo-formed (or diffuse) nodules can form iron pans through coalescence (figure 2.1e and f) (Crowther *et al.* 1996, 114). There are two main theories about the formation of iron pans in the natural environment, i.e. without the influence of anthropogenic activities: that pans can form either by redox processes or by podzolisation (Breuning-Madsen and Holst 1992, 82; 1998, 1104; Conry *et al.* 1996, 279; Stucki *et al.* 1988). The formation of iron pans by redox processes involves both vertical and lateral movement, and precipitation of iron oxides along a surface where the movement of water is inhibited, either by reduction of soil pore space, or accumulation of organic matter (e.g. root channels) (Breuning-Madsen and Holst 1992, 82; 1998, 1104; Courty *et al.* 1989, 180; van Breemen 1988). Podzolisation most commonly occurs in acidic, well-drained sandy soils under coniferous or heather vegetation in temperate climates (Blume 1988; Breuning-Madsen and Holst 1998, 1104; Lundström *et al.* 2000a). There is a plethora of literature that focuses on the different processes involved in podzolisation (Bergelin *et al.* 2000; Breuning-Madsen and Holst 1992; Buurman and Jongmans 2005; Conry *et al.* 1996; Egli *et al.* 2002; Eusterhues *et al.* 2005; Giesler *et al.* 2000; Gustafsson *et al.* 1995; Gustafsson *et al.* 2000; Ilvesniemi *et al.* 2000; Jansen *et al.* 2004, 2005; Karltun *et al.* 2000; Lundström *et al.* 2000a; Lundström *et al.* 2000b; Melkerud *et al.* 2000; Mirabella *et al.* 2002; Olsson and Melkerud 2000; Riise *et al.* 2000; Stützer 1998, 1999; van Breemen *et al.* 2000; van Hees *et al.* 2000a; van Hees *et al.* 2000b; Wilson 2001; Zysset and Berggren 2001). Generally, the process of podzolisation involves the leaching of iron-organic complexes eluviated from the topsoil being illuviated further down the profile (Blume 1988; Breuning-Madsen and Holst 1992, 82; de Coninck and Righi 1983; Lundström *et al.* 2000a; van Breemen and Buurman 1998). The organic matter will be precipitated in the upper part of what is termed the spodic horizon and the iron will be precipitated further down the spodic horizon (*ibid*).

However, there are various theories about the mechanisms involved in podzolisation and the four main theories are: the fulvate theory, the proto-imogolite theory, the fulvate-bicarbonate theory and the low molecular weight (LMW) organic acid theory (Buurman and Jongmans 2005; Jansen *et al.* 2005, 537; van Breemen and Buurman 1998, 245). The fulvate theory involves the dissolving of iron and aluminium from primary and secondary minerals by unsaturated fulvic acids in the topsoil, which are then mobilised and translocated down profile and precipitated in the B horizon upon the saturation of organic molecules through metal

complexation (Buurman and Jongmans 2005, 71; van Breemen and Buurman 1998, 245). The proto-imogolite theory involves the transportation of iron and aluminium as silicate sols into the B horizon where they precipitate as amorphous allophane and imogolite, followed by subsequent adsorption of mobile humus (*ibid*). The fulvate-bicarbonate theory involves two stages of profile development: the first is the *in situ* formation of imogolite/allophane in the Bs horizon by a carbonic acid weathering process; the second is by the precipitation of fulvic acid on the aluminium rich precipitates in the Bs horizon (Buurman and Jongmans 2005, 72). These processes can occur sequentially or simultaneously (*ibid*). Finally, the LMW organic acid theory is a variation upon the fulvate theory and suggests that LMW organic acids are responsible for the transport of iron and aluminium into the B horizon and that the precipitation of these ions is the result of the microbial breakdown of the carrier (Buurman and Jongmans 2005, 72; van Breemen and Buurman 1998, 245). In addition, it has been suggested that the reduction of iron compounds within the soil can also influence its mobility (Buurman and Jongmans 2005; Skjemstad *et al.* 1992).

The reason for so many theories about podzolisation is that the horizonation of these soils varies depending on climate and altitude (see Buurman and Jongmans 2005 for a full review). However, the consistent model that each of these theories contains involves mobilisation, transportation and precipitation of minerals, such as iron and aluminium, and organic matter, namely humus (*ibid*). Furthermore, the mobilisation, transportation and precipitation of these substances can result in the formation of iron pans below the albic horizon, along an interface where aerobic and anaerobic conditions exist, and can be due to compaction of the soil pore space or highly acidic conditions resulting from weathering of minerals and the breakdown of organic material and the subsequent release of organic acids (Breuning-Madsen and Holst 1992; Conry *et al.* 1996; Egli *et al.* 2002; Jansen *et al.* 2005). In addition, iron pans can form in podzols through the accumulated deposition of iron, organic matter, and occasionally manganese, as a result of the podzolisation processes outline above (Breuning-Madsen and Holst 1992; Buurman and Jongmans 2005; Conry *et al.* 1996; Jansen *et al.* 2004). Whereas iron pans produced by redox processes can occur rapidly, iron pans produced by podzolisation occur over a long period of time (e.g. 300-500 years, or in some cases 2500-3000 years) (Breuning-Madsen and Holst 1992; Wilson 2001).

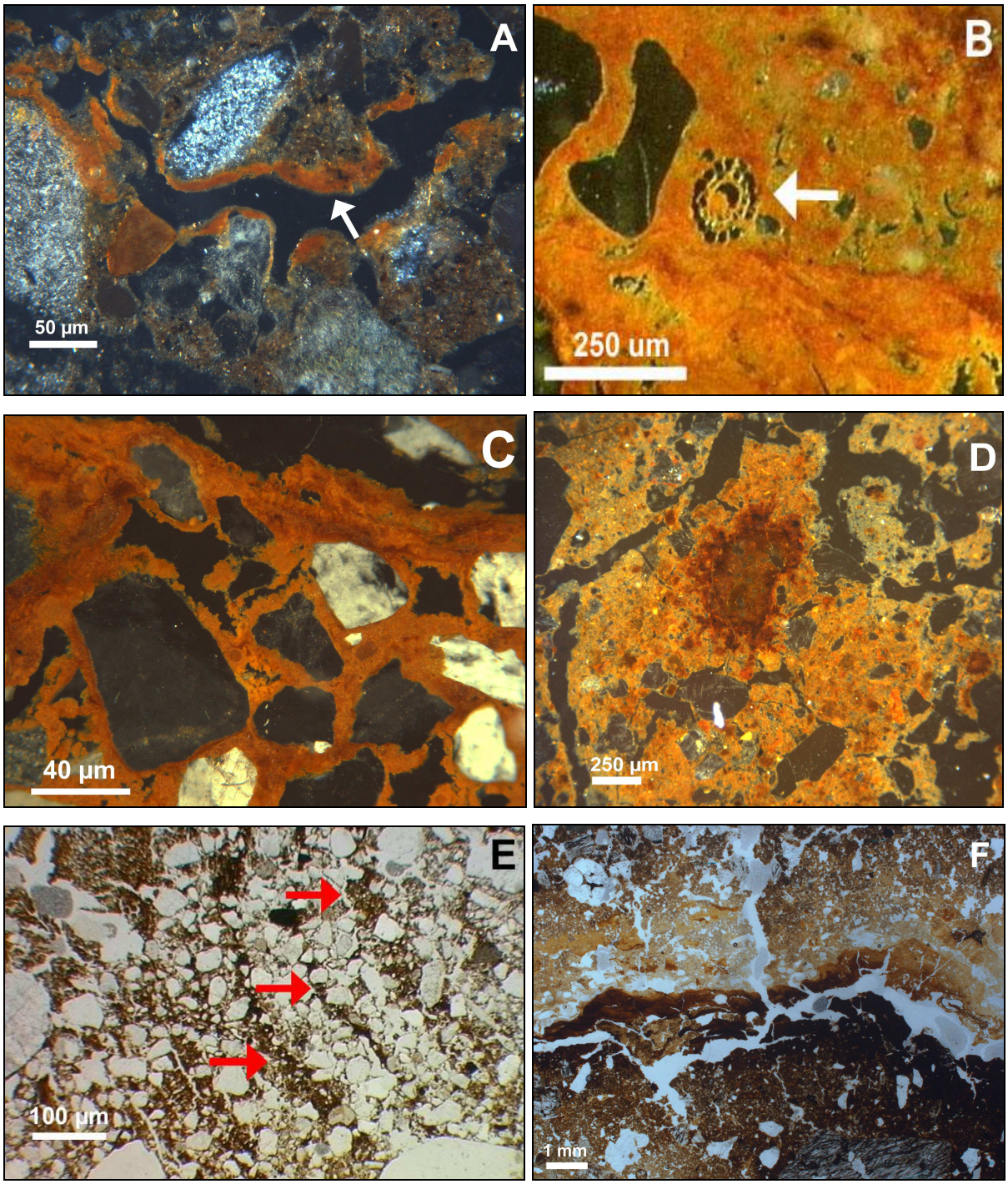


Figure 2.1. Microphotographs illustrating the different types of iron oxide deposition resulting from redox processes. A = Iron oxide coating of void in soil fabric (RL); B = Replacement of organic material by iron oxide (pseudomorph) with cell structure still visible (RL); C = Staining of the soil fabric by iron oxide (RL); D = Neo-formed (or diffuse) iron nodule (RL); E = Iron oxide micro-pans (red arrows) (PPL); F = Undulating iron pan (PPL). RL = reflected light; PPL = plane polarised light.

2.9 Iron Pans and Preservation

Iron pans associated with monuments and features in archaeological sites are a common phenomena in northern Europe, and several studies have examined the formation of iron pans

and the effect they have on the preservation of organic material (Benac 1990; Breuning-Madsen and Holst 1992, 1998; Breuning-Madsen *et al.* 2001; Canti *et al.* 2004; Conry *et al.* 1996; Crowther *et al.* 1996; Gebhardt and Langohr 1999; Macphail and Cruise 1996, 105). Breuning-Madsen and Holst have carried out the most extensive work on iron pan formation in burial mounds in Denmark. Their work includes field investigations (Breuning-Madsen and Holst 1992), chemical analyses (Breuning-Madsen and Holst 1998) and experimental burial mounds (Breuning-Madsen *et al.* 2001). The focus of Breuning-Madsen and Holst's investigations has been to determine the genesis of the iron pans found in burial mounds and to understand the role the iron pans have in the preservation of the organic record (Breuning-Madsen and Holst 1992, 1998; Breuning-Madsen *et al.* 2001). Breuning-Madsen and Holst found that the iron pans present in the burial mounds of Denmark were produced by redox processes, and that the iron pan created an anaerobic environment within the core, which preserved the organic record (*ibid*).

Breuning-Madsen and Holst (1992, 85) argued for two different stages of construction for burial mounds in Denmark. The first stage is the construction of a densely packed core of poorly drained soil over well-drained subsoil in which a log coffin is placed (*ibid*). The soil may be saturated during construction to obtain the compaction required, or it may be constructed with naturally wet soil (*ibid*). The second stage involves a less dense mound covering the core, which is referred to as the mantle. The mantle is created immediately after the construction of the core from a well-drained drier soil (*ibid*).

These conditions are conducive to iron pan formation by redox processes as oxygen remaining in the core is depleted early in the decay sequence by micro-organisms (*ibid*). Following this, the iron present in solution then travels to areas high in oxygen, such as the mantle and subsoil beneath the mound (*ibid*). At these locations the iron oxidises becoming immobile (Breuning-Madsen and Holst 1998, 1104). Eventually, a build up of iron oxides causes mobile iron to move laterally and oxidise forming an iron pan around the edge of the core of the mound (Breuning-Madsen and Holst 1992, 85). At this stage the core is anaerobic and maintains this state due to the iron pan preventing oxygen entering the core. The anaerobic environment then preserves any organic material remaining within the core (*ibid*).

Another experimental analysis of iron pan formation is that of Crowther *et al.* (1996, 114) who found signs of panning within the chalk bank at Overton Down, but only nodules and compound nodular formations were present in the buried soil. It is suggested this is due to the

shallow well-drained soils within the earthwork and that key factors in iron pan formation may be the presence of clay-rich and poorly drained soils (*ibid,* 113). Also, little replacement of organic material by iron (otherwise known as pseudomorphs) was observed within the buried soil, which suggests that the environment within the earthwork is not conducive to rapid iron formation, but given time this may change (*ibid,* 114).

The presence of iron pans in archaeological sites, such as Silbury Hill in Wiltshire and the Medieval Motte at Werken, Belgium, are two examples of the effects of iron panning and subsequent organic preservation (Canti *et al.* 2004; Gebhardt and Langohr 1999). Silbury Hill is the largest man-made monument in Europe and is the centre of much controversy about its purpose and the nature of its construction (Field 2002). It is thought to have been constructed in the late Neolithic and there is evidence for activity on and around the monument until at least the Early Medieval period (*ibid*). There have been many archaeological excavations carried out on the monument to discern its purpose but to date no clear conclusions have been made (*ibid*). These excavations have left their mark on Silbury Hill and have contributed to the delicate preservation state it is in today (Canti *et al.* 2004; Field 2002). Most significant to the detriment of Silbury Hill are the shaft excavation, carried out by Colonel Drax and the Duke of Northumberland in 1776, and the tunnel excavations to the centre of the monument carried out by Merewether in 1849, and by Atkinson in 1968 (Field 2002; Harding 2004). It is on this premise that Canti *et al.* (2004) investigated the preservation of Silbury Hill and recommended conservation action be taken to preserve the monument. Iron pans are ubiquitous at Silbury Hill in the turf stack and old land surface but not in the upper chalky rubble above, or the solid chalk below (*ibid*, 9). The iron pans present are due to compaction of the weight of the hill and the change in soil texture with the fine silt and clay of the turf stack providing a semi-impermeable zone, which provided anaerobic conditions ideal for organic preservation. Preservation in the turf stack and the capping deposits (mixture of topsoil and chalk), was very good with "fragments of insects, molluscs, moss and other plant macroscopic remains" (*ibid,* 10). As the pH remained alkaline, this preservation was attributed to the anaerobic conditions of these sediments and iron panning as evidence of localised redox conditions (*ibid*). Likewise, at the Medieval Motte at Werken, localised zones of anaerobic and aerobic conditions were observed.

The Medieval Motte at Werken is a 6m high man-made flat hill made up of at least 8 construction phases and 9 occupation layers (Gebhardt and Langohr 1999, 595). The presence of the hill resulted in the local rising of the natural groundwater table causing some areas to

become anaerobic and others to remain aerobic (*ibid*). The boundary between the anaerobic and aerobic zones was demarcated by an iron-manganese pan (*ibid*, 613). In one of the occupation layers a wooden floor was evident and had been deposited on leached sandy subsoil (*ibid*). The floor was obliquely cut by the anaerobic/aerobic boundary resulting in differential preservation (*ibid*). In the reduced zone, the wooden floor was very well preserved, although blackened by some organic decay, whereas in the oxidised zone, only organic residue remained in the sandy soil (*ibid*). Unlike Silbury Hill, the iron pan formation at Werken was not associated with any sedimentary or depositional layer, but was instead the result of the rise in natural groundwater levels around the motte (Canti *et al.* 2004; Gebhardt and Langohr 1999). Gebhardt and Langohr (1999, 615) suggest that an accumulation of clay caused a change in porosity at the boundary of the groundwater table, which triggered cycles of reducing and oxidising conditions, resulting in the development of the iron-manganese pan, "trapping the percolating rainwater in the central part of the motte hill, resulting in a zone of permanently intense reducing conditions". The Medieval Motte at Werken provides a rare insight into the differential preservation of organic material between aerobic and anaerobic conditions and highlights the importance of research into preservation and conservation of organic material in archaeological sites.

The observations made by Breuning-Madsen and Holst (1992; 1998), Breuning-Madsen *et al.* (2001), Crowther *et al.* (1996), Canti *et al.* (2004) and Gebhardt and Langohr (1999) have made valuable contributions to the discussion of iron pan development and organic preservation, but have not addressed preservation aspects of an archaeological site with reference to other types of iron deposition, such as staining, neo-formed nodules and coatings. The presence of iron staining, neo-formed nodules and coatings in the soil environment may be used as an indicator of oxidation-reduction cycles (Courty *et al.* 1989, 180; Limbrey 1975, 73). As iron oxides provide additional oxygen for bacteria in an aerobic environment, where iron is present bacterial activity persists (Limbrey 1975, 73). It is only in anaerobic environments (e.g. within iron pans) that preservation subsists (*ibid*). Consequently, the presence of iron staining, nodules and coatings may be used as an indicator that oxygen has been introduced into an anaerobic environment. Furthermore, as the presence of neo-formed nodules and staining are the result of different rates of oxygen being introduced into the buried environment, these characteristics can be used to determine the existing hydrological environment of the site and to assess the preservation potential of archaeological organic material (cf. French *et al.* 1999; French 2004; French and Heathcote 2003; Macphail and Cruise 1996, 105; Welch and Thomas 1998, 16).

The effect of iron deposition, such as staining, neo-formed nodules and coatings in soils/sediments, on the preservation of palaeoenvironmental and archaeological records has not been addressed in the literature so far. This research project intends to investigate how different types of iron deposition, represented by different oxidation environments, can serve as indicators of preservation conditions within an archaeological site.

2.10 RESEARCH PARAMETERS AND LIMITATIONS

In order to assess how the deposition of iron oxide can be used as an indicator of oxidation, and, in turn, be used to predict the level of organic preservation in archaeological sites, a comparative database is developed using data from oxidation experiments on four different sites in Britain. The aim of these experiments is to identify iron oxide characteristics that are unique to each experiment. Due to the complexity of iron movement and deposition in the soil environment, not all processes are measured. This project focuses on the physical and chemical processes of iron oxide deposition, and regrettably, the expertise to include the effects of microbial activity remains outside the scope of this research.

Further, there are various types of iron oxides present in soils and sediments, including hematite, goethite, lepidocrocite, magnetite, maghemite and ferrihydrite (Schwertmann (1988) and Schwertmann and Taylor (1989) in Loeppert and Inskeep (1996)). All these occur in ferric form with the exception of magnetite, which occurs in both ferric and ferrous forms (Loeppert and Inskeep 1996, 639). Of these iron oxides, magnetite is predominantly found in reduced or slightly weathered soils (*ibid*, 640), and ferrihydrite is most commonly found in soils that undergo rapid oxidation and reducing fluctuations (Schwertmann and Cornell 2000, 16). In order to identify the type of iron oxide present in the soils used for the comparative database, more sophisticated analysis is required, such as microprobe analysis or scanning electron microscopy. As each of the iron oxide minerals has unique crystal structures and morphological characteristics dependant on how rapidly the ferrous iron transforms into ferric iron, these techniques could confirm the presence of a particular type of iron oxide (Stucki *et al.* 1988). Unfortunately, the use of microprobe analysis or scanning electron microscopy was not viable for this research project. It is proposed that a combination of magnetic susceptibility, ICP-AES, and information gleaned from the current literature will provide enough data to infer the type of iron present in the soils used for this project (see appendix A, table A-2). It is reasonable to assume that the majority of iron oxide present in the soils from

the comparative database is likely to be ferrihydrite or lepidocrocite due to the environments of the selected sites, as discussed in the following section.

Although relative percentages for soil porosity of the comparative database samples are noted during micromorphology analyses to account for changes in soil structure between the control samples and the experimental samples, a more quantitative method using image analysis would be ideal. However, due to the sheer volume of samples collected during the research project and the time constraints involved, this analysis has not been carried out.

2.11 Background to the Comparative Database Sites

Four sites within Britain were selected for the development of the comparative database (Figure 2.2). Each site has a different soil/geology type, ecological and hydrological environment, and range from acidic to alkaline conditions. The background and description of relevant properties for each site follows.

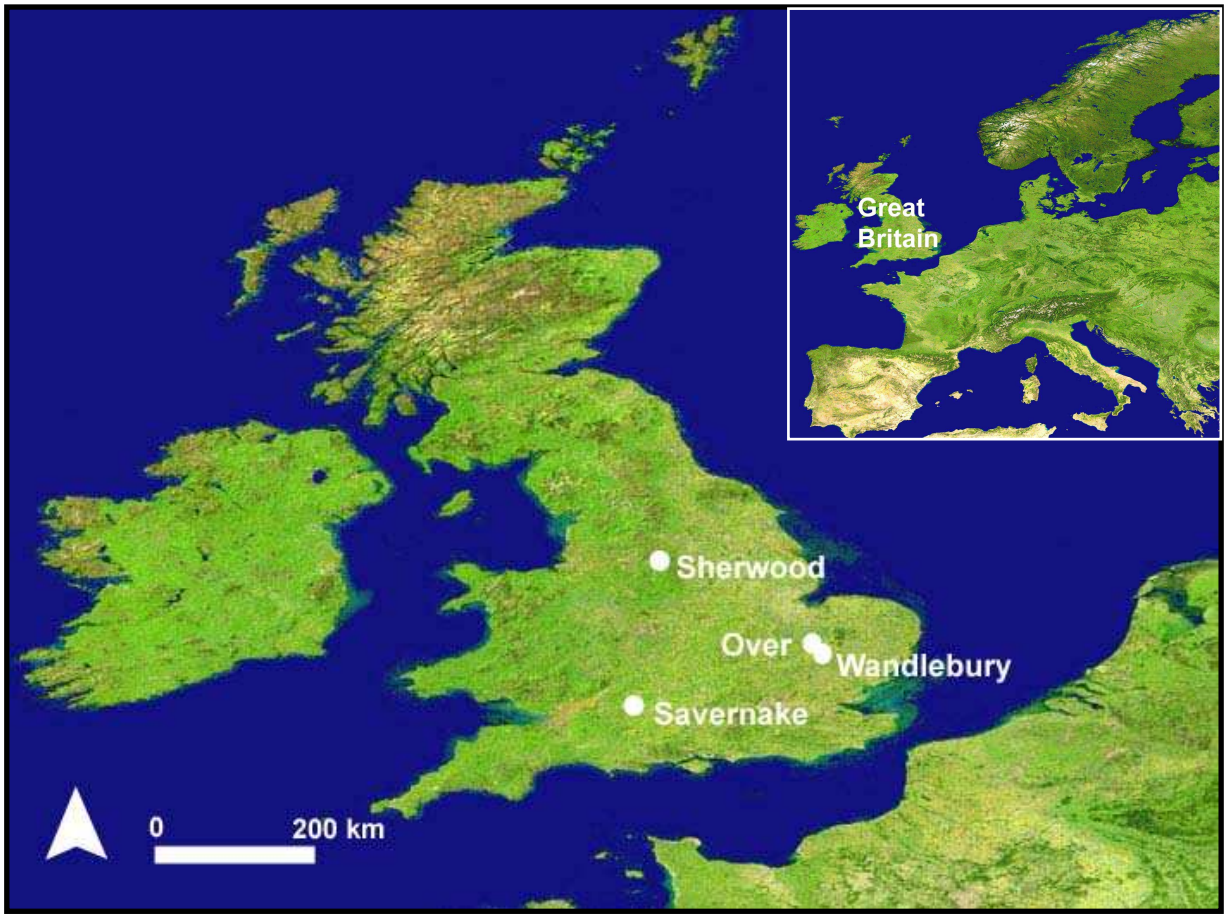


Figure 2.2. Map showing the location of sites selected for the development of the comparative database (maps adapted from http://www.globe-images.net/europe-image.htm).

2.11.1 Over

The comparative database site at Over is situated in the alluvial floodplain of the lower Great Ouse valley in Cambridgeshire between the villages of Over and Willingham to the south, and Bluntisham and Earith to the north (TL 390725) (French and Heathcote 2003). The site is approximately 800m north of a Late Bronze Age enclosure (which will be discussed in chapter 5) and is part of a hydrological monitoring programme, which has been in place since 1994 as a result of gravel extraction being carried out at the site (French *et al.* 1999). Groundwater abstraction made necessary in order for the quarry company (Hanson) to reach the gravel beds has resulted in the dramatic lowering of the groundwater table from approximately 1.2m to 1.5m below the ground surface to 5m below the ground surface (French 2004). The soil profile is a circum-neutral alluvial brown earth and, in the strict sense of the word, an alluvial brown earth is non-calcareous, loamy, with a brown or reddish friable subsurface horizon (Courtney and Trudgill 1976, 100). The site is under arable cultivation, however, due to the depth of the peat and alluvial overburden, this activity has had little effect on the underlying soil profile. Beneath *c.* 30-80cm of peat and alluvial overburden is free-draining, fine loamy sand overlying sandy Devensian river gravel and Oxford Clay. Apart from the peat and alluvium, the soil contains very little organic material and iron mottling is present throughout, but particularly noticeable in the B horizon. The site's proximity to a well documented archaeological excavation (figure 2.3), and its inclusion in a hydrological monitoring program, makes it an ideal choice for this project and includes a dominant soil/geology type (figure 2.5) and environment (figure 2.4) found in archaeological sites in Britain.



Figure 2.3. Satellite image of the quarry site at Over. The white star indicates the Over CDB site (image adapted from *Google Earth*).



Figure 2.4. View of the arable cultivation field in the background and the CDB test pit marked by an orange peg (and white arrow) in the foreground.



Figure 2.5. Soil profile of the Over CDB test pit, with approximately 30cm of peat and alluvial overburden capping free-draining, fine loamy sand.

2.11.2 Wandlebury

Similar to Over, the Wandlebury comparative database test pit is in close proximity to a well-documented archaeological site, the Wandlebury Iron Age ringwork (French *et al.* 2005b). The site is situated approximately 6.5km southeast of Cambridge and is "positioned towards the northern end of the undulating chalk ridge of the Gog Magog Hills overlooking the Cam valley and the fens beyond" (*ibid*, 1). The CDB test pit is located at the south end of Varley's field adjacent to the ringwork (TL 4940 5343) (figure 2.6). The CDB site is a pastoral landscape (figure 2.7a) with sheep regularly grazing in the field as well as clear evidence of mole activity (figure 2.7b). The profile is a shallow alkaline soil with a humic A horizon, overlying a silty loam B horizon with many chalk inclusions, on top of a chalk substrate, and is typically known as a rendzina (figure 2.8). A rendzina is defined as soils that have a dark-coloured surface horizon, are rich in organic matter with a high base status, and directly overlie a highly (>40%) calcareous rock or sediment (Bridges 1997, 74). In addition to its locality to the nearby well-documented archaeological site, Wandlebury was selected for its soil type and environment, firstly, as it is representative of the soils and environments of many archaeological sites in southern England, and secondly, as rendzinas typically are not affected by groundwater fluctuations, this site can be used to identify the effects of precipitation as a source for redox processes as opposed to groundwater fluctuations.

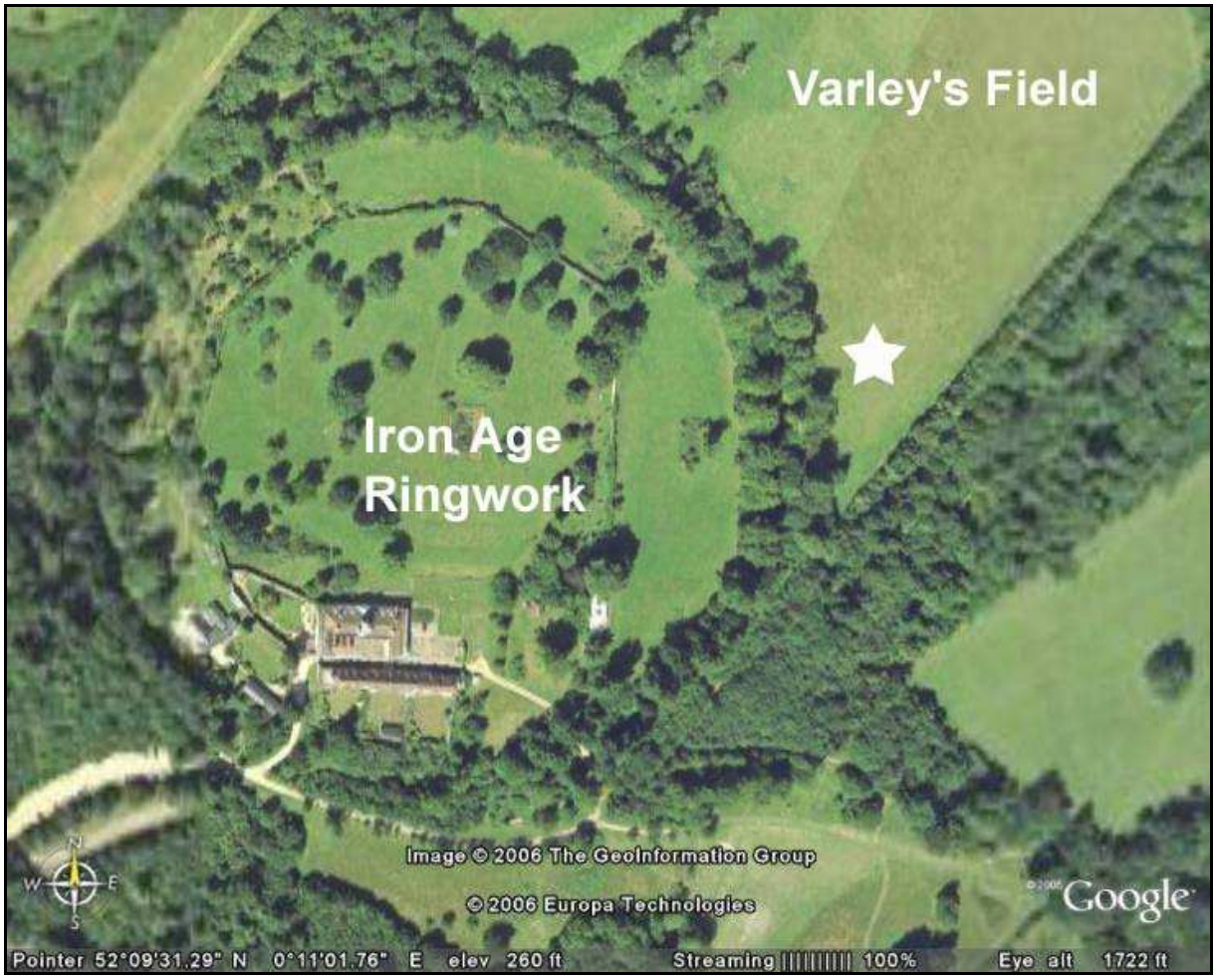


Figure 2.6. Satellite image of the Wandlebury Iron Age ringwork and the CDB test pit site (white star). Image adapted from *Google Earth*.



Figure 2.7a and b. Photographs of the CDB test pit site at Wandlebury. On the left (A), sheep grazing in the field and on the right (B) mole activity (black arrow) and the test pit site (white arrow).

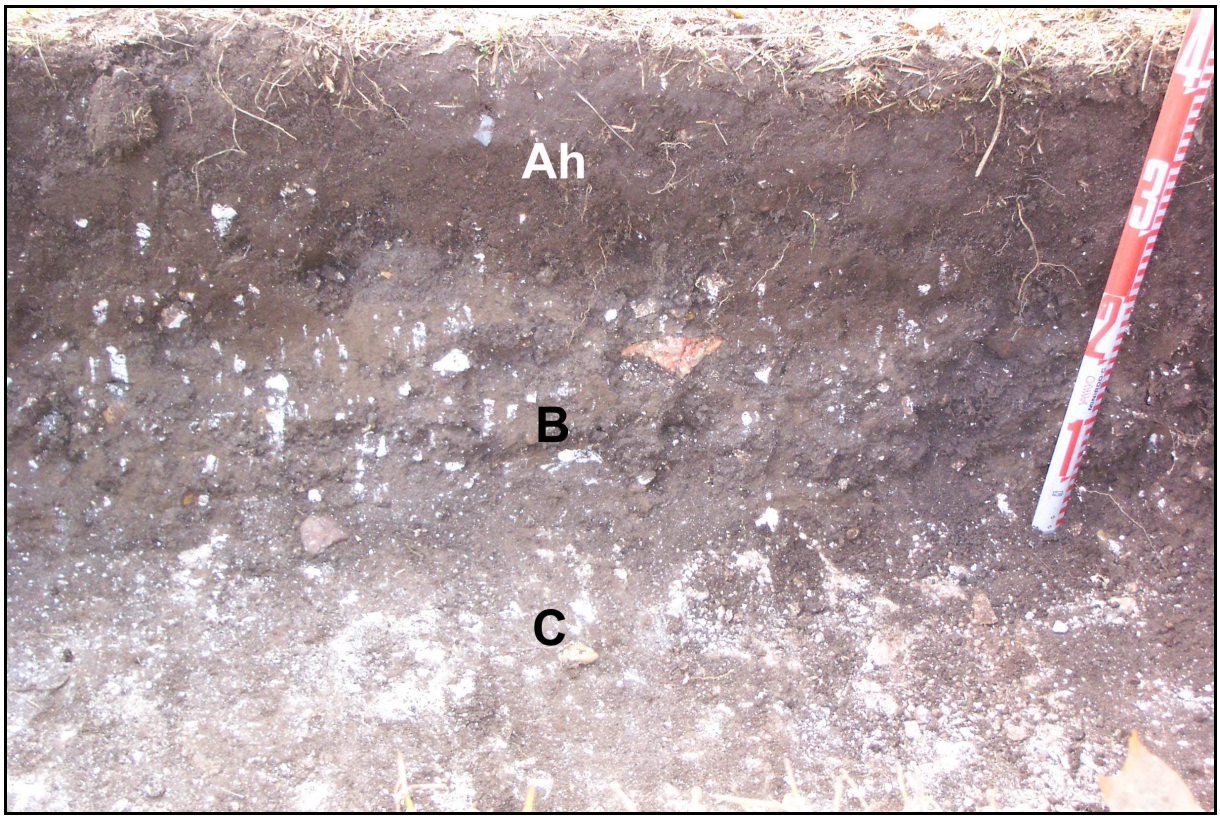


Figure 2.8. Soil profile of the Wandlebury CDB test pit – a typical rendzina sequence.

2.11.3 Savernake

Savernake forest is in southwest England approximately 25km northwest of Swindon (SU 4055 1888). Savernake is a young Oak forest (figure 2.9), approximately 50 years old, overlying a poorly drained acidic argillic pelosol. An argillic pelosol is a slowly permeable non-alluvial clayey soil that cracks deeply in dry seasons with a brown, greyish or reddish blocky or prismatic subsurface horizon of clay accumulation, normally non-calcareous, and usually slightly mottled (Courtney and Trudgill 1976, 101). The floor of the forest includes bramble, grass, moss and leaf litter (figure 2.10) and the fluctuations of the groundwater table vary from season to season. In January the test pit regularly filled up with water, whereas in October 2003 (after a very dry summer) the clay was so hard that the mattock bounced off the surface! The soil profile is organic-rich silty clay overlying a dark yellowish brown silty clay B horizon and a light olive grey clay-rich B/C horizon with iron mottles (figure 2.11a and b). The forest is regularly visited by the locals on horseback and on foot with their dogs. Muntjac deer are also regular visitors. This site is part of an EU/ICP (International Co-operative Programme) and Forestry Commission research project, which monitors the effects of

pollution and other environmental factors on British forests. All meteorological data for this site is supplied by Forestry Services and will be discussed at length in chapter 4.



Figure 2.9. Satellite image of Savernake forest with the CDB test pit site marked by a white star (image adapted from *Google Earth*).



Figure 2.10. Savernake Forest in spring – the CDB test pit is in the opening between the trees (white arrow).

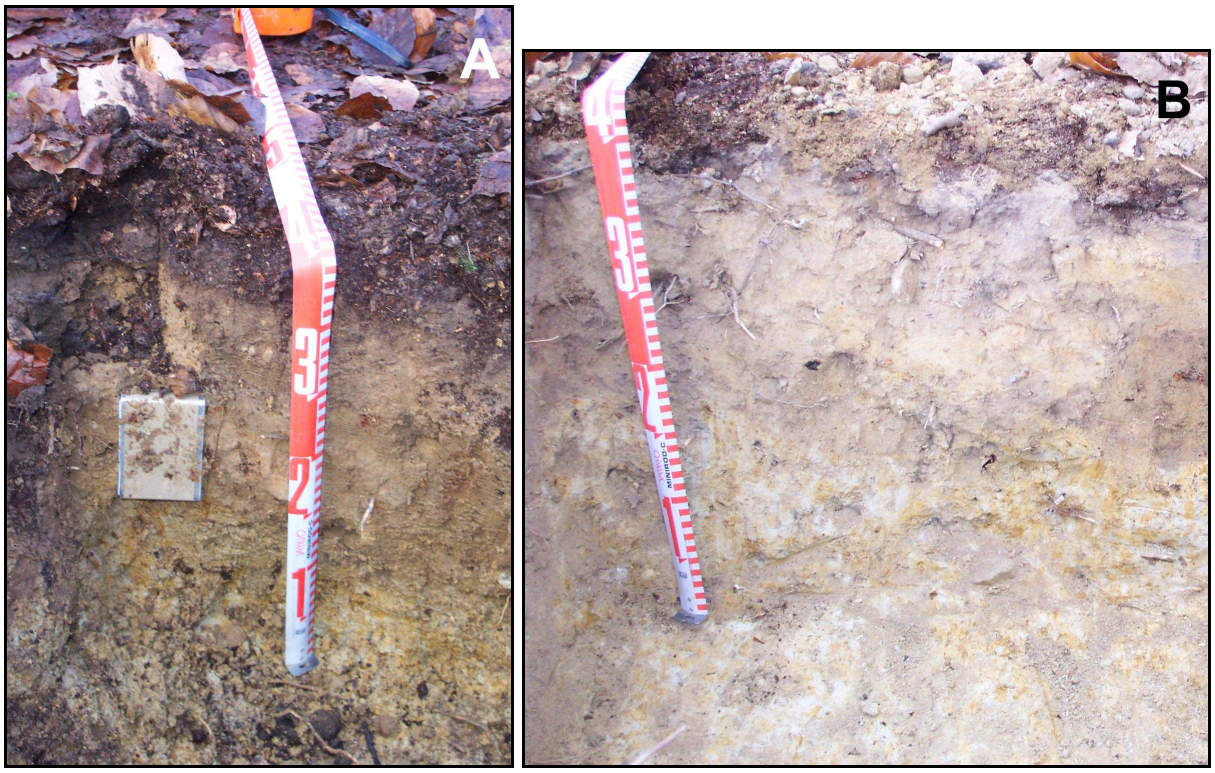


Figure 2.11a and b. Soil profile at Savernake with a Kubiëna tin in place for sampling (see chapter 3) on the left (A). Note the difference between the profile in January (A) and the profile in October (B).

2.11.4 Sherwood

This site has been named by the Forestry Commission and for continuity will be referred to as Sherwood for this research project. The site of Sherwood (SK 163 908), contrary to popular belief, is not *the* Sherwood Forest known through folk tales of Robin Hood and his Merry Men, but is actually located approximately 25km northwest of Sheffield and is situated in the Upper Derwent Valley National Park (figure 2.12). The test pit is on the side of a steeply dissected valley (figure 2.13a) with a stream at the base of the valley that leads into the Derwent Reservoir. It is a Scots Pine forest (figure 2.13b) overlying an acidic brown podzolic soil. A brown podzolic soil is acidic and contains a podzolic B horizon (which contains an enrichment of OM, iron and aluminium) but does not have an albic E horizon (Bridges 1997, 47). The soil profile consists of an organic horizon (O), a humic horizon (H) followed by a silty clay horizon with very fine rootlets (Ae), overlying a loamy clay Bst horizon and a clay loam B/C horizon (figure 2.14). Although every effort is made by Forestry Services to keep sheep from grazing at the site, sheep were abundantly present on more than one occasion during sample collections. As with Savernake, Sherwood is part of an EU/ICP and Forestry Commission environmental monitoring programme and all meteorological data for Sherwood is courtesy of Forestry Services.

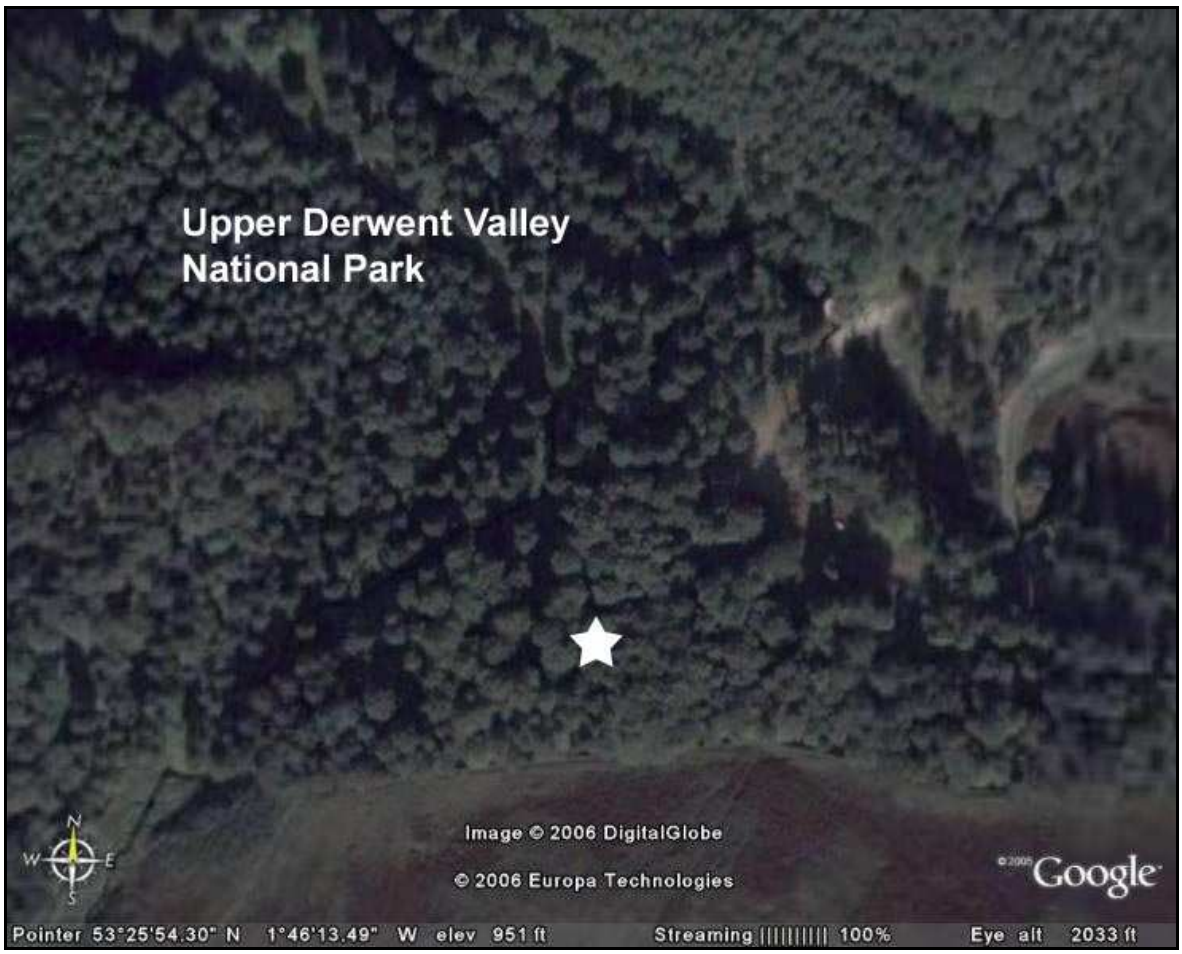


Figure 2.12. Satellite image of the Upper Derwent Valley National Park and the Sherwood CDB site, indicated by a white star (image adapted from *Google Earth*).

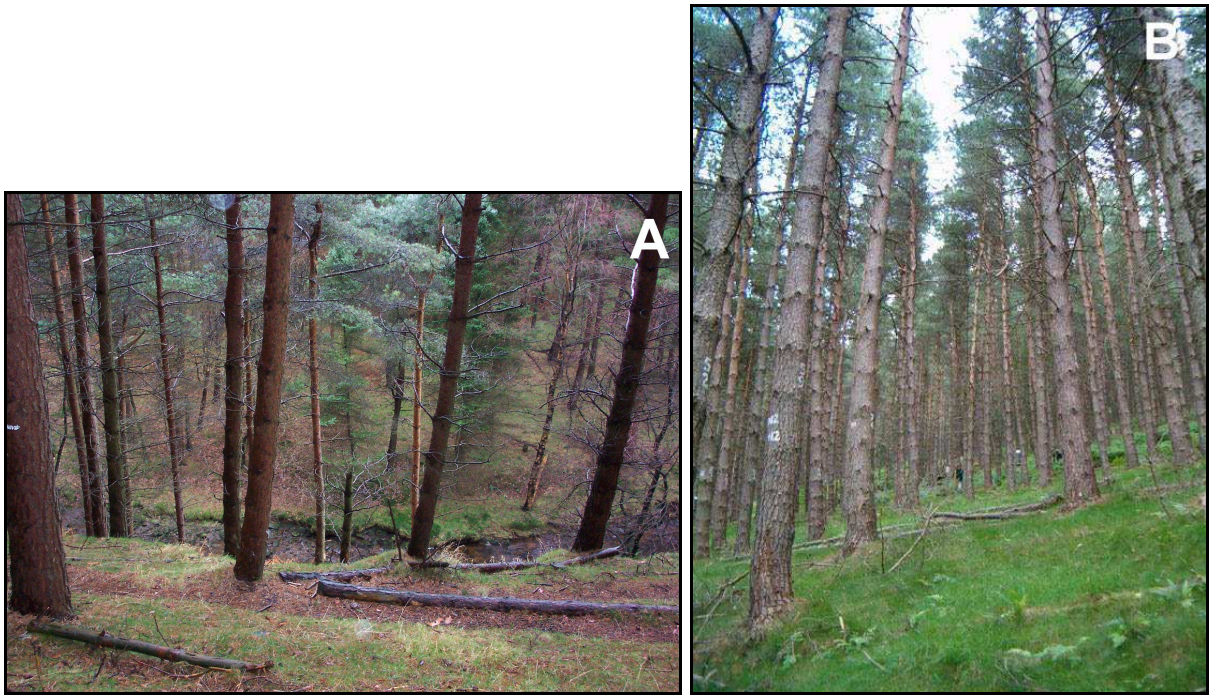


Figure 2.13a and b. The left photograph (A) depicts the small stream at the base of the steep valley slope and the photo on the right (B) depicts the environment of the Sherwood CDB test pit.



Figure 2.14. The soil profile for the Sherwood CDB test pit – a brown podzolic soil.

2.12 SUMMARY

In order to understand the link between iron oxide and preservation, it was first necessary to review the processes involved in site formation, site preservation, processes of oxidation and iron oxide deposition, and how these processes affect the preservation of organic material in archaeological sites. This chapter reviewed past and current research on archaeological site formation processes, both physical and anthropogenic post-depositional processes, and how these processes can affect the preservation of organic material in archaeological sites. The crucial element responsible for fluctuations between anaerobic and aerobic conditions is redox and the role this process plays in the variable preservation conditions of organic material. With influxes of oxygen into an anaerobic environment, the transformation of ferrous iron to ferric iron, and its subsequent deposition, leaves behind distinctive patterns, which can be related to specific hydrological conditions within the buried environment. These deposition patterns include iron coatings, iron replacement of organic material (pseudomorphs), iron staining, neo-formed (or diffuse) iron nodules and iron pans. Various research projects investigated the benefits of iron pan formation for the preservation of organic material in archaeological sites by the development of localised anaerobic conditions. They have

illustrated just how important the role of physical, chemical and biological processes can be in relation to iron oxide deposition, and the delicate and complex issues that surround the preservation of organic material in archaeological sites. In light of this, my research aims to introduce the depositional patterns of iron oxide as a valuable indicator of oxidation in the buried environment through experiment and the development of a comparative database. This database will then be used as a tool to gauge the level of preservation expected for archaeological organic material within four different soil environments across Britain. The sampling strategy, laboratory experiments and analyses for the comparative database are outlined in the following chapter.

– 3 –

METHOD: EXPERIMENTS WITH OXIDATION

3.1 INTRODUCTION

As we have seen in the last chapter, environments that exist outside ideal organic preservation conditions (i.e. waterlogged or arid environments) have been largely ignored due to the complexity of the preservation environment. While there have been attempts to investigate the effects of oxidation on the preservation of the artefacts themselves, the effects of oxidation on the soils, and how these changes can affect the preservation environment, have not been studied in relation to identifying a tool for gauging the preservation of organic material in archaeological sites. By examining the changes these soils go through under different oxidising environments, it is possible to identify the level of preservation of organic material that can be expected in an archaeological site. As discussed earlier, iron oxide can be used as an indicator of oxidation and by examining the different types of iron oxide deposition in the soils, using a combination of bulk and soil micromorphological analyses, it is possible to identify the type of hydrological environment for that site, and hence the level of preservation that can be expected for organic archaeological material. The development of a comparative database (CDB) based on the deposition of iron oxide in soils and how this relates to variations in oxidising conditions, provides a platform for identifying hydrological environments within archaeological sites. This chapter outlines the sampling strategy for the comparative database, the field and laboratory protocols used, and the statistical analyses undertaken during the course of this research project.

3.2 SAMPLING STRATEGY FOR THE COMPARATIVE DATABASE (CDB)

To reiterate, the main research aims for this project are:

- First, to identify and characterise a range of features expressed by iron oxide as a sensitive indicator of oxidation in soils and sediments.
- Second, to develop a comparative database (CDB) through oxidation experiments on soils of different soil/geology types within Britain.
- Third, to test this database using archaeological sites of similar soil/geology types to the CDB, in terms of the organic material preserved in relation to the patterns of iron oxide deposition

The first aim was addressed in the previous chapter, which highlighted a range of pedofeatures, including diffuse iron nodules, iron staining, iron coatings, iron replacement and iron pans, which are further defined in section 3.4. The second is addressed in this, and the following, chapter by designing oxidation experiments replicating different oxidising conditions, namely rapid versus slow oxidation, which is explained further below and in section 3.3. Finally, the third aim is addressed in chapter five where sediments from five different archaeological sites were sampled and analysed, the methodology for which is outlined below in section 3.7.

Four sites within Britain were selected for the compilation of the CDB. Within these sites, four different modern environments and soil/geology types are represented. Savernake is an oak forest with acidic argillic soil, Sherwood is a pine forest with acidic brown podzolic soil, Wandlebury is a pastoral site on a calcareous rendzina and Over is a circum-neutral agricultural site on an alluvial brown earth. Sample excavations were carried out seasonally in October 2003, January 2004, April 2004 and July 2004 to account for seasonal variation in the experiments. A 100cm x 60cm x 40cm test pit was excavated and backfilled at each site in the first season in October 2003, which was re-excavated in the following seasons, each time cutting one wall of the pit back to expose an undisturbed surface for micromorphology sampling. Each season, three sets of micromorphology profile samples were taken along with two groups of small bulk samples. The soil micromorphology samples were taken using Kubiëna tins of two sizes, medium (9 x 6.5cm) and small (7.5 x 5cm), and were sampled so as to represent the entire exposed soil profile. The bulk samples were taken at 5cm intervals down the soil profile. Soil moisture readings were taken in the field by the TDR 300 moisture meter (see appendix B for calibration of the meter). Readings were taken at the surface and at 5cm intervals down through the soil profile. In-field soil descriptions and sketches were also

undertaken using Munsell charts, along with digital photos. Meteorological and soil water data were obtained from Forestry Services and MORECS. Table 3.1 summarises the sampling and laboratory methods used for this research project.

Table 3.1. Summary of the methods used for this research project, including sampling and laboratory analyses. Undisturbed samples refer to samples used for soil micromorphological analyses.

<table>
<tr><th rowspan="2">SAMPLING</th><th rowspan="2">LABORATORY</th><th rowspan="2">UNDISTURBED SAMPLES</th><th rowspan="2">BULK SAMPLES</th><th colspan="2">ANALYSES</th></tr>
<tr><th>UNDISTURBED SAMPLES</th><th>BULK SAMPLES</th></tr>
<tr><td rowspan="4">Seasonal collection, four times a year;
Undisturbed = one sample from each soil horizon;
Bulk = sample taken every 5cm down the soil profile</td><td colspan="3">Three groups:</td><td rowspan="4">Soil micromorphology using guidelines set out by Stoops (2003) and Bullock et al (1985); see section 3.4</td><td rowspan="4">ICP-AES
PSD
LOI
MS
pH
EC
Redox
VWC
Moisture content</td></tr>
<tr><td>Oven dried</td><td>72 hours at 40ºC</td><td>72 hours at 40 ºC</td></tr>
<tr><td>Air dried</td><td>Three months at room temperature</td><td>Three months at room temperature</td></tr>
<tr><td>Control</td><td>Acetone replacement</td><td>N/A
See section 3.3</td></tr>
</table>

3.3 LABORATORY EXPERIMENTS

In order to test the effects of rapid oxidation versus slow oxidation on the deposition patterns of iron oxide, two experiments were designed. The first was to replicate rapid oxidation and its effects on the oxidation of iron in soils and sediments. As discussed in chapter two, the rapid oxidation of soils and sediments results in an increase in diffuse iron nodules, as the rapid removal of moisture from the soil/sediment will cause the rapid oxidation of iron (Bohn *et al.* 2001, 108; Gerrard 1992, 96). In order to maintain an environment which rapidly removes moisture from the soil while introducing oxygen, one group of soil samples were placed in an oven at 40ºC for a period of 72 hours, following the advice of Murphy (1986) for thin section preparation. The second experiment was designed to replicate slow oxidation with fluctuations in moisture, and therefore, slow down the rate of oxidation. As discussed in chapter two, the result of slow oxidation in soils/sediments is the staining of the groundmass (see below) by iron oxide (Ralston 1979, 424; Sparks 1995, 159). In order to represent an environment with slow oxidation, a second group of soil samples were air dried for three months in the laboratory with varying levels of humidity, maintaining fluctuations in atmospheric moisture, thereby slowing the rate of oxidation (Sparks 1995, 159). This method was chosen based on the protocol of thin section preparation used by the McBurney Geoarchaeological Laboratory at the University of Cambridge. In summary, the samples collected from the field were divided into three groups for the soil micromorphology samples: 1) oven dried, 2) air dried and 3) control; and two groups for the small bulk samples: 1) oven

dried and 2) air dried. The control samples for the micromorphological analyses were collected as representative of the natural, in-field soil conditions at each of the sites without the influence of the oxidation experiments. The bulk samples do not include a control group as the protocols for the bulk analyses require the sediment to be dry. This is further explained below.

3.3.1 Micromorphology Samples

The control samples were treated with acetone replacement (appendix C) before impregnation to minimise the effects of drying out (e.g. shrinkage). As this method uses acetone (an ingredient of the resin mix) to replace the moisture in the soil, the blocks can be impregnated with the resin mix and successfully processed. The oven dried samples were dried in an oven at 40ºC over a 72 hour period in order to assess the effects of rapid oxidation on the soils. The air dried samples were dried out on the laboratory shelves at room temperature for a period of three months to assess the effects of slow oxidation on the soils.

The micromorphology samples were impregnated with a crystic resin mixture following Murphy (1986), at the McBurney Geoarchaeology Laboratory, Department of Archaeology, University of Cambridge (appendix C). In addition, the resin mixture was thinned to ensure better impregnation for more clay-rich material (appendix C). A total of 66 thin sections were processed by the author in the McBurney Geoarchaeology Laboratory (appendix C), while the remaining 140 samples were sent to CSIRO Australia.

3.3.2 Small Bulk Samples

As each of the bulk analyses required the sediment to be dry, the moisture content of the soil was taken prior to the drying out experiments. This was measured by calculating the bulk density, using a volumetric sampler for a fixed volume of soil ($5cm^3$), and the value (expressed as g/cm^3) was then calculated into a percentage (%) of moisture for comparisons to moisture readings taken after the oxidation experiments (see appendix F). This measurement assessed the quantity of moisture within the soil and provided supporting evidence for the in-field readings taken by the TDR 300 moisture meter. The oven dried samples were treated in the same way as the micromorphology samples, as were the air dried samples. Each of the samples for bulk analyses, once dry, were ground down using a mortar and pestle and passed through a 2mm sieve.

The bulk analyses included particle size distribution (PSD), loss on ignition (LOI), magnetic susceptibility (MS), hydrogen ion activity (pH), electrical conductivity (EC), and redox potential (Eh). I conducted each of these analyses in both the McBurney Geoarchaeology Laboratory, Department of Archaeology, and the Physical Geography Laboratory, Department of Geography, University of Cambridge. The samples were also sent to ALS Chemex for inductively coupled plasma – atomic emission spectroscopy (ICP-AES) for total iron (Fe) and manganese (Mn), using an aqua regia digestion.

3.4 SOIL MICROMORPHOLOGY

Soil micromorphology is a technique originally developed in soil science to examine naturally occurring soil processes. It enables a systematic analysis of soil/sediment structure and specific features in the soils/sediments. It is both a qualitative and quantitative method for describing the relationships between such features in relation to soil-forming processes. Soil micromorphology is used by archaeologists as it provides the opportunity for detailed investigation of soils and sediments and their depositional and post-depositional processes, *in situ*, and over extended timescales. Soil micromorphology has been applied in various contexts including the examination of buried soils, domestic floors and other ancient surfaces (Boivin 2000; Gebhardt and Langohr 1999; Matthews *et al.* 1997), barrow mounds and feature fills (Courty *et al.* 1989; French 2003; French *et al.* 2005a; Gebhardt and Langohr 1999). Such examinations reveal evidence of construction techniques, human interaction with the landscape, and utilisation of space. The samples also provide specific soil or sediment characteristics, including iron oxide features and other indicators of soil chemical and moisture regimes (Cornwall 1953, 1958; Courty *et al.* 1989; Crowther *et al.* 1996; Dalrymple 1958; French *et al.* 2005a; French 1992; French and Heathcote 2003; Macphail and Cruise 1996).

In this research project, soil micromorphology is used to identify different types of iron oxide deposition present, the percentage of iron oxide and where the iron oxide is within the profile. Data from micromorphology can provide information that indicates how and why iron formed in conjunction with its effect on soil structure, development and preservation of the site. Following the guidelines in the pedofeature section of Bullock *et al.* (1985) and Stoops (2003), the deposition, quantity and location of iron oxide in the thin sections were

systematically described. In addition, details of soil structure, porosity, bioturbation, and organic material and its preservation condition were noted.

In order to efficiently analyse each sample a database was set up in *Microsoft® Excel*, which accommodated the following categories:
Groundmass incorporates the coarse and fine mineral components of the soil/sediment, porosity and any other constituents of the soil, which are not pedofeatures (Stoops 2003, 91). There are several sub-categories including coarse-fine ratio, coarse-fine related distribution, microstructure, nature of fine material, birefringence-fabric (*b*-fabric), percentage of porosity and dominant porosity type.

Coarse-fine ratio and coarse-fine related distribution describe the ratio between the coarse mineral component (e.g. quartz grains) and the fine mineral component (e.g. clay), and how they are related. For example, if a sample had a single spaced porphyric related distribution then it would have quartz grains surrounded by dense clay with little space between each of the quartz grains, i.e. a single grain size space between each of the quartz grains. The ratio limit is set prior to analyses and for my research the limit is set at 20µm, i.e. the upper limit for fine material is 20µm.

Microstructure describes the relationship of aggregates and voids within the groundmass and more detailed descriptions of this terminology can be found in Stoops (2003, 68ff). The nature of fine material describes the composition of the fine material, for example, silty clay, or iron-rich clay. The *b*-fabric or birefringence fabric "describes the origin and the patterns of orientation and distribution of interference colours in the micromass" or fine material, e.g. clay (Stoops 2003, 95). Percentage of porosity and dominant type of porosity are important parts of describing the structure of the soil/sediment and follow the terminology of Stoops (2003, 63ff).

Iron nodules are features within the soil that are not part of the normal soil fabric, i.e. they are pedofeatures, which "are more or less equidimensional" and "are not related to natural surfaces or voids and… do not consist of single crystals or crystal intergrowths" (Stoops 2003, 117). For each sample I have noted the size range of nodules present and for each nodule I have noted its shape, the strength of impregnation and the type of boundary, following Stoops's (2003, 117ff) categories. Using these categories it is possible to determine whether the nodules were formed *in situ* by redox processes (e.g. diffuse boundary) or

whether they have been transported through the soil (e.g. sharp boundary), and therefore, are more likely to have come from a parent material (Stoops 2003, 118).

Iron staining of the groundmass is often observed in the field as rusty mottles or streaks but because of the difference in scale from the field to the thin section, I have noted it as iron staining of the soil fabric or groundmass and it is distinct from iron nodules, which are more localised impregnations of the groundmass by iron. A percentage of iron staining in each horizon is noted for all samples.

Iron coatings and hypo-coatings are, for my research, iron-rich coatings of grains and pores; either intrusive pedofeatures, which are in direct contact with the edges of the grains and pores (coatings), or matrix pedofeatures, which are not in direct contact with the edges of grains or pores (hypo-coatings). See Stoops (2003, 106) for further definition.

Iron pseudomorphs, or replacement of organic material by iron oxide, is a process by which iron completely replaces the organic material whilst maintaining the cell structure and is most likely the result of repeated redox (i.e. wetting and drying) cycles. When iron is present in its soluble form (ferrous iron) it can be an essential nutrient to plant material and some of this iron may be used by the respiration processes of the plant, especially with the aid of fungi, such as mycorrhizae (Carrasco *et al.* 2006; Clark and Zeto 1996; Eyre 1968; Gobat *et al.* 2004; Jenkinson 1981; Pande and Tarafdar 2004; Trudgill 1977; Wood 1989). However, in some cases, the level of soluble iron present in the soil may become toxic to the plant and the iron becomes oxidised by bonding with the cellular structure of the plant material, forming pseudomorphs (Bullock *et al.* 1985; Stoops 2003). This can occur when, for example, groundwater rich in soluble iron rises and saturates the soil containing plant material, and after a period of time, recedes, giving the soluble iron an opportunity to oxidise and/or bond with any organic material present (Rowell 1981). However, it must be noted that as organic material decomposes (e.g. roots), the iron held within the organic material is released, giving a reddish hue to the organic material (Babel 1981). This can sometimes be confused with iron replacement of organic material but they are two very separate processes. The size range and location of pseudomorphs present were noted.

Iron pans can form by either redox processes or by podzolisation processes (Breuning-Madsen and Holst 1992, 82; 1998, 1104; Conry *et al.* 1996, 279; Stucki *et al.* 1988). They are often clear, strong bands of iron (and in most cases manganese), which can mask the soil

fabric. In most cases, the iron pans are noted in the field but are sometimes presented as micropans. Micropans are visible in thin section and often encompass small pockets of the soil fabric as a result of localised chemical changes within the soil. The size range, strength of impregnation and location were noted for each occurrence.

Charcoal is identified by its opaque, dull lustre under reflected light and its angular to subangular shape. Larger pieces of charcoal may maintain cell structure. The presence of charcoal is categorised by size: less than 100µm and greater than 100µm.

Amorphous Organic Material is separated into two categories: amorphous punctuations and amorphous organic matter. Amorphous punctuations are defined as "small dark or opaque grains, about 1µm" in size (Stoops 2003, 89). Amorphous organic matter is any organic material without identifiable cell structure of any size greater than 1µm.

Celled Organic Material includes lignified tissues, parenchymatic tissues, phlobaphene-containing tissue, plectenchyma and pollen. Lignified tissues are "composed of elongated, thick-walled originally emptied cells" (Stoops 2003, 89). Parenchymatic tissue "are composed of more or less equant thin-walled cells" and phlobaphene-containing tissue has cells which are "equant or oblate, the walls thin or thick" with phlobaphenes contained in the cell lumen (Bullock *et al.* 1985, 78; Stoops 2003, 89). Phlobaphenes are "products of oxidation and polymerisation of tannins" and are often found in tissues such as bark (Bullock *et al.* 1985, 78). Plectenchyma include fungal tissues, such as sclerotia, which are identifiable by their characteristic cellular structures (Bullock *et al.* 1985, 78). For each celled organic material category, frequency, size range, location, degree of preservation and association with iron features were noted.

Other Pedofeatures include evidence of bioturbation and presence of excrements (e.g. mites) and excretions (e.g. earthworms) for which size range and location were noted (see Stoops 2003 for more information).

Each thin section sample was divided into a $5mm^2$ grid and the total number of squares for each horizon was noted. A total of six squares for each sample were selected for analysis according to the spreadsheet categories. Three samples were randomly selected from the upper portion of the sample and three squares were randomly selected from the lower portion

of the section in order to cover any variation or change within the thin section. If there was more than one soil horizon within a section then six squares were selected from each horizon.

The presence of iron nodules, coatings and hypo-coatings were analysed by point counting, while the remaining categories were analysed by percentage frequencies. All categories were analysed within the six randomly selected squares for each horizon with the exception of iron staining, iron pans and porosity, which were analysed by recording percentages from the whole horizon for each category. The counts and frequencies from each of the six squares were averaged and multiplied by the total number of squares in their corresponding horizon to generate representative values for the samples. Except where percentage frequencies were taken from the whole horizon, all frequencies and point-counting were noted at x100 magnification using a combination of cross polarised light (XPL), plane polarised light (PPL) and reflected light (RL).

3.5 BULK ANALYSES

Bulk analyses were used in conjunction with soil micromorphology as a quantitative method to discern how oxidation affects organic preservation by focusing on the presence of iron oxide, and how its (re-)deposition is associated with mineral and organic fractions of the soils/sediments. Such analyses included ICP-AES, particle size distribution, loss on ignition, magnetic susceptibility, pH, electrical conductivity and redox potential.

Inductively coupled plasma – atomic emission spectroscopy (ICP-AES) first requires the samples to go through digestion by aqua regia. This involves using a 3:1 mixture of hydrochloric and nitric acids in order to dissolve the organic material in the soils and release the "free" elements (for this study, Fe and Mn) into solution (http://www.alschemex.com/learnmore/learnmore-techinfo-principles-sampdecomposition.htm).

The following explanation for how ICP-AES works has been taken directly from the ALS Chemex website:

> In plasma emission spectroscopy, a sample solution is introduced into the core of an inductively coupled argon plasma (ICP) at a temperature of approximately 8000°C. At this temperature all elements become thermally excited and emit light at their characteristic wavelengths. This light is collected by the spectrometer and passes through a diffraction grating that serves to resolve the light into a spectrum of its constituent wavelengths. Within the spectrometer, this diffracted light is then collected by

> wavelength and amplified to yield an intensity measurement that can be converted to an elemental concentration by comparison with calibration standards. This measurement process is a form of atomic emission spectroscopy (AES) (http://www.alschemex.com/learnmore/learnmore-techinfo-principles-analyticalmethodologies.htm).

ICP-AES was used in my research to obtain quantitative data from the samples for iron (Fe) and manganese (Mn). In conjunction with other techniques the results from ICP-AES can provide valuable information about how these elements move through the soil. For example, variations in quantity of Fe and Mn present in samples collected at different depths can suggest processes such as eluviation/illuviation and reducing-oxidising cycles. While the author is aware that other methods of chemical extraction exist, such as using pyrophosphate and dithionite extraction, which enable selective extraction of different types of iron present in the samples, including organo-iron complexes and iron-mineral compounds (Borggaard 1988), near total extraction was used for this project due to the limited time available and the sheer quantity of samples collected. With these constraints, an extraction method which was 'multipurpose' was selected, i.e. aqua regia.

Particle size distribution (PSD) measures the percentages of various sizes of particles in the soil/sediment. In this research project, PSD, using a Malvern laser particle-sizer, was used to determine the amount of clay present in each of the samples: as discussed in the last chapter, iron oxide often travels with clay through the soil by eluviation/illuviation processes. PSD, in combination with ICP-AES, is used to determine how the iron is moving through the soil profile and the process by which the iron is deposited. The protocol used for this analysis follows the protocol outlined by the Department of Geography (appendix D), in addition to which hydrogen peroxide was used to first digest the organic material in each of the samples.

Loss on ignition (LOI) measures the amount of moisture, organic material, calcium carbonate and silicate residue in soil/sediment samples based on decreasing sample weight (Nelson and Sommers 1996). LOI provides information on the location of the iron in the soil. For example, a particularly high organic content may indicate that the iron is concentrated in the organic component of the soil (Courty *et al.* 1989, 180/1; Gerrard 1992, 96/7), however, a high calcium carbonate content may result in reduced levels of iron in the soil (Crowther 1996, 108; Limbrey 1975, 73). By determining the percentage of moisture, organic material, calcium carbonate and silica in each of the samples, it is possible to infer where the iron oxide may have formed and, combined with other techniques, identify iron oxide deposition processes. It is important to note that LOI was carried out after the drying out experiments so that the percentage of water in each of the samples is a measure of difference between oven

drying and air drying. Further, references made to %OM from LOI throughout this thesis are not actual percentages of organic matter present; instead, these values are considered to be proxies for organic matter as determined by LOI. The LOI protocol is presented in appendix D.

Magnetic susceptibility (MS) measures the response of soil to a magnetic field (Lapidus 1990, 336). Iron oxide (and manganese oxide) has a strong magnetism that dominates other magnetic minerals and can be measured in soil using MS (Aitken 1969, 681; Longworth and Tite 1977, 3). MS can identify minerals in the soil with magnetic qualities and provide a reading of the amount of these minerals in each sample, which are converted into universally accepted measurement units, SI units per unit mass (Dearing 1999). This technique does not measure all forms of iron in the soil but measures iron that has a higher magnetic susceptibility (Clark 1996; Loeppert and Inskeep 1996). MS is used here as a complementary technique to ICP-AES for quantitative measurements of iron and manganese in the soils/sediments. The protocol used for MS can be found in appendix D.

Hydrogen ion activity (pH) provides information on the degree of acidity/alkalinity, element mobility, phosphorus availability and microbial activity (Goudie 1990, 146). pH was used to measure the level of acidity/alkalinity in the soil to determine what effect this could have on the preservation of the site. Relative to my research, the concentration of iron in its solution phase can also be affected by pH levels. The samples were measured using a 1:5 dilution and the protocol can be found in appendix E.

Electrical Conductivity (EC) measures the ability of the soil solution to conduct electricity and is used to determine the quantity of soluble salts in the soil (Courtney and Trudgill 1976, 62; Rhoades 1996, 417). EC can be used as an indicator of processes, such as leaching within the soil profile, which can occur as a result of redox processes. Further, EC is influenced by soil moisture, particle size and organic matter (cf. Carroll and Oliver 2005). As with pH, the samples were measured using a 1:5 dilution and the protocol can be found in appendix E.

Redox potential (Eh) measures the reducing and oxidising potential of the soils/sediments. If the value is positive then the sample has oxidising potential, if negative, then it has reducing potential (Patrick *et al.* 1996, 1255). Redox potential can be affected by other fractions of the soil/sediment such as iron, manganese, organic material, moisture content and pH (Dragun and Baker 1979, 132). The redox measurements taken for this research project were not taken

in the field but were taken after the oxidation experiments were carried out. While this was done for consistency in method, the readings are not true measurements of the redox potential for each of the samples. As a result, redox is used in this study as a complementary technique to a variety of bulk analyses that were carried out here. As with pH and EC, the samples were measured using a 1:5 dilution and the protocol can be found in appendix E.

3.6 STATISTICAL ANALYSIS

The data collected from the various bulk and soil micromorphological analyses were collated and run through a number of statistical analyses using *SPSS* 13.0, *Psimpoll* and *Microsoft® Excel*. The first step was to confirm that all the data were normally distributed by using a one sample Kolmogorov-Smirnov test (K-S test) (Field 2005). If the result was greater than 0.05 ($p>.05$) then the data were normally distributed (*ibid*). For the bulk analyses data, means and standard errors were used to assess the variation between seasonal data collections. Each experiment group and each site were analysed separately. Correlations were run on all the data: for those that were normally distributed, Pearson's correlation was used, and for those that were not normally distributed, Spearman's correlation was used (*ibid*).

For the soil micromorphology data, a different approach was taken as the database for the description was set up to reveal patterns of variability and similarity between each category. For the most part frequencies were recorded in percentage form for each category but where actual numbers present were recorded, for example, for iron nodules and coatings, percentages were calculated so as to compare like with like. Means and standard errors were then used to assess seasonal variation between samples, and each experiment group and site were analysed separately. Tables and graphs were used to demonstrate the relationship between the different categories recorded.

3.7 THE ARCHAEOLOGICAL SITES

Five archaeological sites, of similar soil/geology type to the CDB sites, were also sampled in order to test the effectiveness of using iron oxide as a sensitive indicator of oxidation in soils, and how this oxidation affects the preservation of organic material. Micromorphological and bulk samples for bulk analyses were collected from each site from various archaeological features and buried soils. The sites include the Late Bronze Age enclosure at Over, which is on an alluvial brown earth, the Iron Age ringwork at Wandlebury on a rendzina, the Romano-

British site at Marcham-Frilford on an argillic brown soil, the Iron Age Enclosures at Sutton Common on a podzolic soil, and the Bronze Age field systems at Shovel Down, also a podzolic soil.

The micromorphological samples were brought back to the McBurney Laboratory for acetone replacement, impregnation and processing by the author. All the archaeological samples for micromorphological analyses were acetone replaced so as to reduce the effects of additional oxidation of the sediments, such as shrinkage and additional iron oxidation. The bulk samples for bulk analyses were air dried as the sample preparation and analyses required the sediment to be dry; moisture content was measured prior to drying the samples. The analyses carried out on both the micromorphology and bulk samples were identical to those carried out on the samples from the CDB sites, including the categories identified for the soil micromorphological analyses. Six 5mm^2 squares were randomly selected from each of the units identified in the thin sections and analysed according to the categories outlined in section 3.4 above.

The data for the bulk analyses are displayed in table format for each site, as are the organic material, iron coatings, iron pans and iron replacement of organic material identified by soil micromorphological analysis. The results for iron coatings and iron nodules have been transformed from total counts to percentages so as to make them comparable to the other types of iron deposition. Iron nodules and iron staining have been identified as highly informative for the effects of oxidation in soils, and the data are presented as bar graphs in chapter five.

3.8 SUMMARY

This chapter described the sampling strategy, experimental framework and the laboratory methods applied to the non-archaeological samples collected in order to compile the CDB. Four different non-archaeological sites were selected for experimental analysis. Each site was chosen for its soil type, environment and availability to meteorological data. Over is a circum-neutral alluvial brown earth in an agricultural environment, Wandlebury is a calcareous rendzina in a pastoral environment, Savernake is an acidic argillic soil under an oak forest and Sherwood is an acidic podzolic soil under a pine forest.

Three sets of profile samples were collected from each site on a seasonal basis (four collections over a one year cycle) for micromorphological analysis. Additionally, two groups of loose samples were collected at 5cm intervals down profile for bulk analyses. Oxidation experiments were conducted replicating the effects of different rates of oxidising conditions. The samples were then analysed using a soil micromorphological database and bulk analyses, which included ICP-AES, particle size distribution (PSD), loss on ignition (LOI), magnetic susceptibility (MS), pH, electrical conductivity (EC) and redox potential (Eh). The resulting data were then run through a number of statistical programs to compile the CDB, the results of which will be presented in chapter four.

Five archaeological sites of similar soil/geology type to the CDB sites were chosen to test the applicability of the CDB and were analysed through bulk and micromorphological analyses. These analyses followed the same format as the samples from the CDB, although were not run through the same statistical analyses as the samples collected are not comparable to each other. The results for the micromorphological and bulk analyses for the archaeology sites are displayed in tables and graphs and are presented and discussed in chapter five.

– 4 –

RESULTS PART I: THE COMPARATIVE DATABASE (CDB)

4.1 INTRODUCTION

The development of an effective tool for gauging preservation of archaeological material, which would otherwise be under threat, is essential for the provision of future curatorial advice for archaeologists in Britain. It is first necessary to understand the existing hydrological/oxidation conditions of the site in order to make informed decisions for its conservation, i.e. recording through excavation versus *in situ* preservation. Further, issues of conservation and preservation of archaeological sites remain in the spotlight as the public become more responsive to a past they can see and interact with as opposed to reading about. The development of the CDB provides a tool for gauging the preservation of one category of archaeological material data, that of organic remains.

The previous chapter outlined the sampling strategy and methods used to collect the data for the comparative database. In this chapter, I will present the results for the CDB on a site by site basis beginning with Over, followed by Wandlebury and Savernake, and finishing with Sherwood. First, I will look at the population distribution for each analysis and present the results for each experiment group to examine seasonality influences. These analyses include ICP-AES for total iron (Fe) and total manganese (Mn), particle size distribution (PSD) for %Clay, loss on ignition (LOI) for %Water after the oxidation experiments and %Organic Matter (%OM), magnetic susceptibility (MS), pH, electrical conductivity (EC), redox potential, moisture content (%) measured in the laboratory, and volumetric water content (VWC) from the in-field moisture readings taken by the TDR Moisture Meter. Second, I will present the correlation coefficients for each dataset and experiment group, which will highlight the significant relationships between each of the variables, allowing inferences to be made regarding the processes taking place in the soils.

Third, I will present a summary of the micromorphology analyses for each experiment group with specific reference to porosity, iron oxide deposition and organic material, the details of which can be viewed in appendix F. Finally, I will combine the data from the bulk and soil micromorphological analyses in order to make comparisons between experiment groups for each site, and to highlight the most important characteristics of the CDB as a tool for gauging organic preservation on archaeological sites, in four major geology/soil types.

4.2 OVER

Over is a circum-neutral alluvial brown earth under arable cultivation and as discussed in chapter two, is in close proximity to water abstraction and gravel extraction. The results of the bulk and soil micromorphological analyses follow for each experiment group: oven dried, air dried and for soil micromorphology only, control.

4.2.1 Bulk Analyses Data

As outlined in the previous chapter, a suite of bulk analyses including ICP-AES for iron (Fe) and manganese (Mn), particle size distribution (PSD) for %Clay, loss on ignition (LOI) for %Water and %Organic Matter (%OM), magnetic susceptibility (MS), pH, electrical conductivity (EC) and redox potential were conducted on the oven dried and air dried bulk samples. Moisture content (%) and volumetric water content (VWC) were recorded prior to the oxidation experiments, and meteorological and soil water data was collected from MORECS. The results for each analysis for the oven dried group are presented here, followed by the results for the air dried group.

4.2.1.1 The Normal Curve and Seasonal Variation

The data for each analysis were tested for normal distribution by using a one-sampled K-S test (Field 2005). If the result is $p>.05$, then the data are deemed normally distributed. The results of this test for all the bulk analyses (oven dried group followed by air dried group) are presented in tables 4.1 and 4.2.

Table 4.1. Results of the normal distribution test for the oven dried group across all seasons. The row highlighted in yellow indicates that this group is normally distributed.

One-Sample Kolmogorov-Smirnov Test for Over Oven Dried Experiment Group

		Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox Potential (mV)	Bulk Density (%)	Volumetric Water Content (%)
N		24	24	24	24	24	24	24	24	24	24	24
Normal Parameters [a,b]	Mean	22429.17	83.50	1.21	4.82	.69	1.29	6.78	23.26	167.15	15.00	9.97
	Std. Deviation	1779.47	12.48	.60	2.61	.21	.49	.16	10.43	13.83	7.29	8.95
Most Extreme Differences	Absolute	.12	.24	.23	.19	.17	.23	.13	.18	.10	.10	.19
	Positive	.12	.24	.23	.19	.17	.23	.13	.18	.07	.07	.17
	Negative	-.06	-.16	-.15	-.14	-.09	-.10	-.09	-.11	-.10	-.10	-.19
Kolmogorov-Smirnov Z		.57	1.15	1.15	.92	.85	1.13	.65	.89	.50	.50	.91
Asymp. Sig. (2-tailed)		.90	.14	.14	.37	.46	.16	.79	.41	.96	.96	.37

a. Test distribution is Normal.

b. Calculated from data.

Table 4.2. Results of the normal distribution test for the air dried group across all seasons. Note the row highlighted in yellow.

One-Sample Kolmogorov-Smirnov Test for Over Air Dried Experiment Group

		Fe (ppm)	Mn (ppm)	Magnetic Susceptibilty (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox Potential (mV)	Bulk Density (%)	Volumetric Water Content (%)
N		24	24	24	24	24	24	24	24	24	24	24
Normal Parameters [a,b]	Mean	23391.67	85.71	1.07	5.47	.69	1.27	6.78	28.04	167.35	15.00	9.97
	Std. Deviation	1826.59	7.48	.42	2.30	.18	.32	.11	8.82	9.93	7.29	8.95
Most Extreme Differences	Absolute	.08	.16	.14	.11	.14	.10	.11	.10	.18	.10	.19
	Positive	.08	.16	.14	.11	.14	.10	.10	.10	.11	.07	.17
	Negative	-.08	-.11	-.08	-.07	-.09	-.05	-.11	-.09	-.18	-.10	-.19
Kolmogorov-Smirnov Z		.41	.80	.70	.53	.67	.49	.54	.51	.89	.50	.91
Asymp. Sig. (2-tailed)		1.00	.55	.72	.94	.76	.97	.93	.96	.41	.96	.37

a. Test distribution is Normal.

b. Calculated from data.

Data from both experimental groups for Over are normally distributed as is evident from the row highlighted in yellow (tables 4.1 and 4.2). All of these values are greater than .05. In order to assess seasonal variability at Over, the means and standard errors were calculated for each bulk analysis and experiment group. The results are presented using bar graphs with error bars, as in figures 4.1 to 4.11 below.

Figures 4.1 to 4.9 present the results of each of the bulk analyses for the oven dried and air dried experiment groups. These figures show there is little seasonal variation, as represented by the error bars, and overall, there appears to be little difference between experiment groups. This result is expected as physical properties, such as %Clay, MS, pH, EC, redox and %OM, in the soil are expected to remain constant and not be affected by the oxidation experiments. The results for Fe (figure 4.1) and Mn (figure 4.2) are also expected as the oxidation experiments are not going to increase or decrease the amount of total iron and manganese present in the soils, but will affect the deposition of these minerals in their oxidised states. The results for %Water in the soils after the oxidation experiments show some small variation between experiment groups but nothing that could be deemed statistically significant (figure 4.3). Therefore, given the leaching of finer soil components (clay and organic matter) from the soil at Over (evident in the bulk and soil micromorphological analyses), the predominantly sandy, free-draining soil is less likely to hold moisture under oxidising conditions.

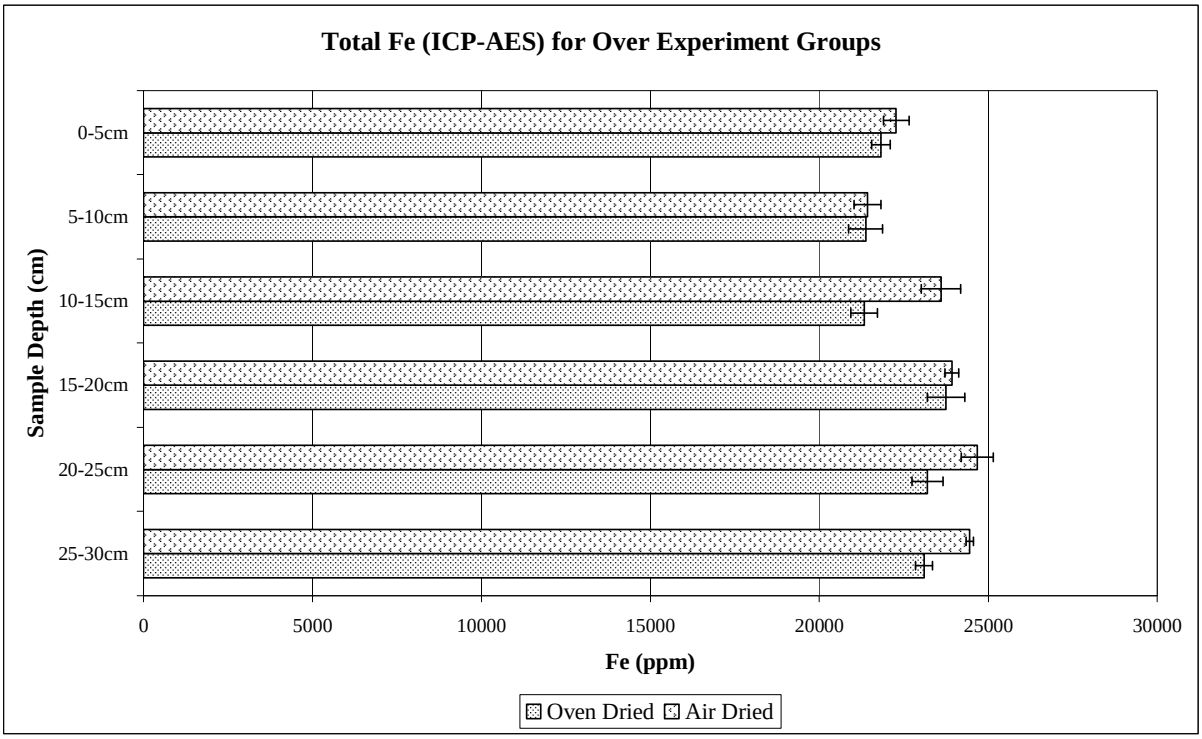


Figure 4.1. Mean and standard error for total Fe (ICP-AES) to determine seasonal variation for both the oven dried and air dried experiment groups.

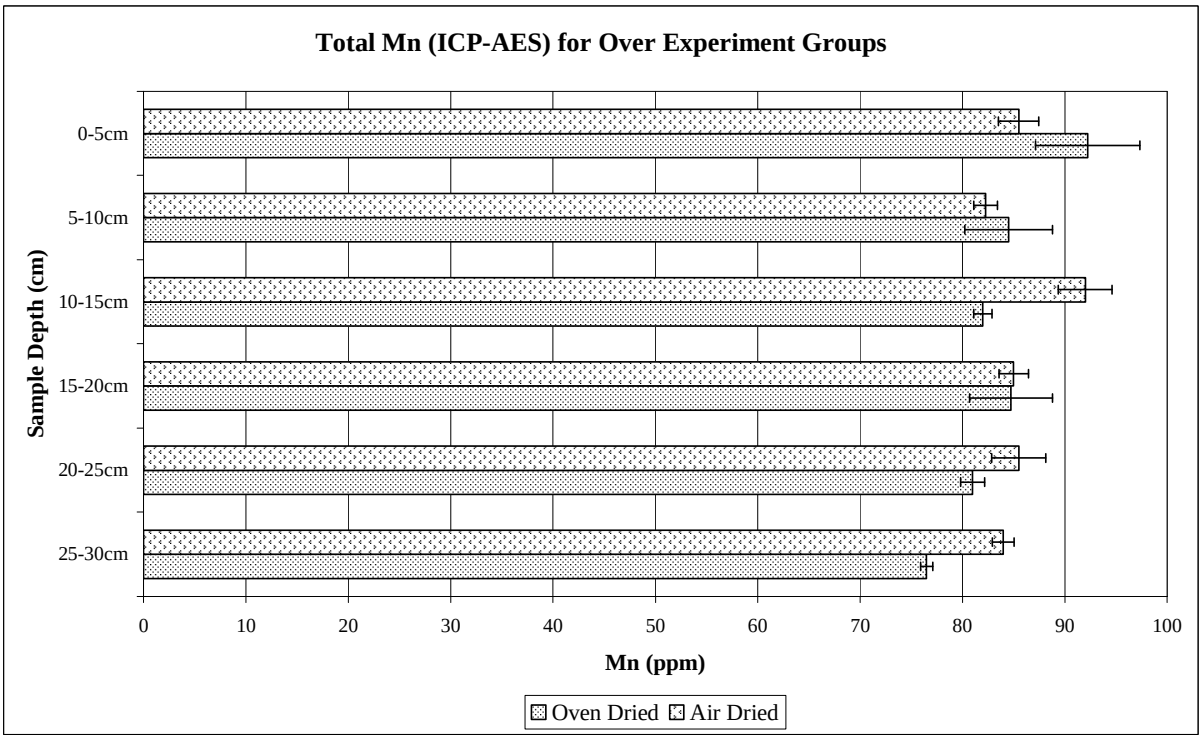


Figure 4.2. Mean and standard error for total Mn (ICP-AES) to determine seasonal variation for both the oven dried and air dried experiment groups.

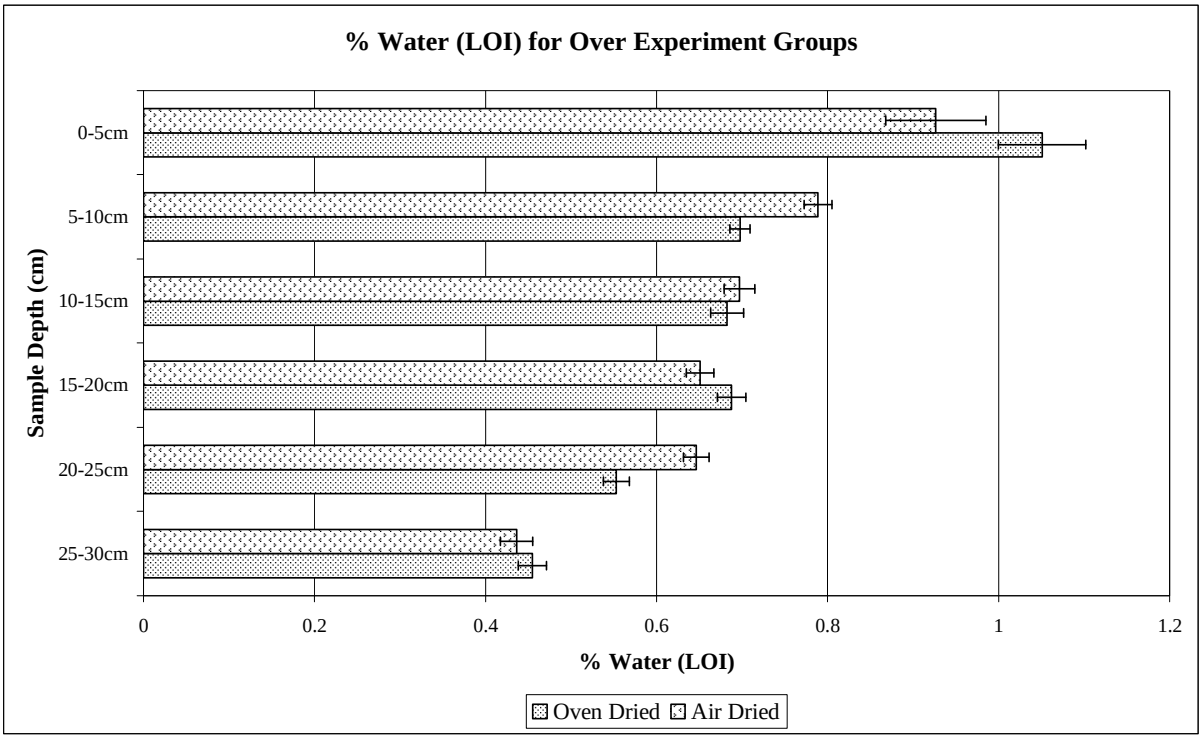


Figure 4.3. Mean and standard error for %Water (LOI) to determine seasonal variation for both the oven dried and air dried experiment groups.

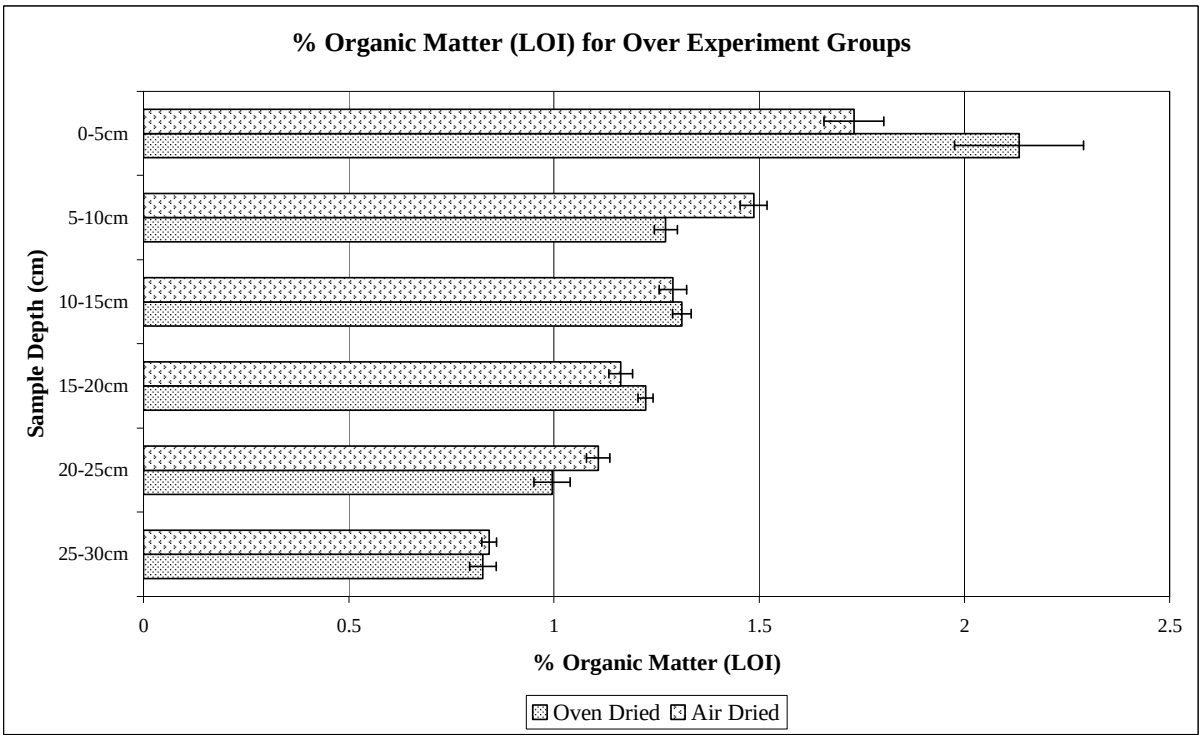


Figure 4.4. Mean and standard error for %Organic Matter (LOI) to determine seasonal variation for both the oven dried and air dried experiment groups.

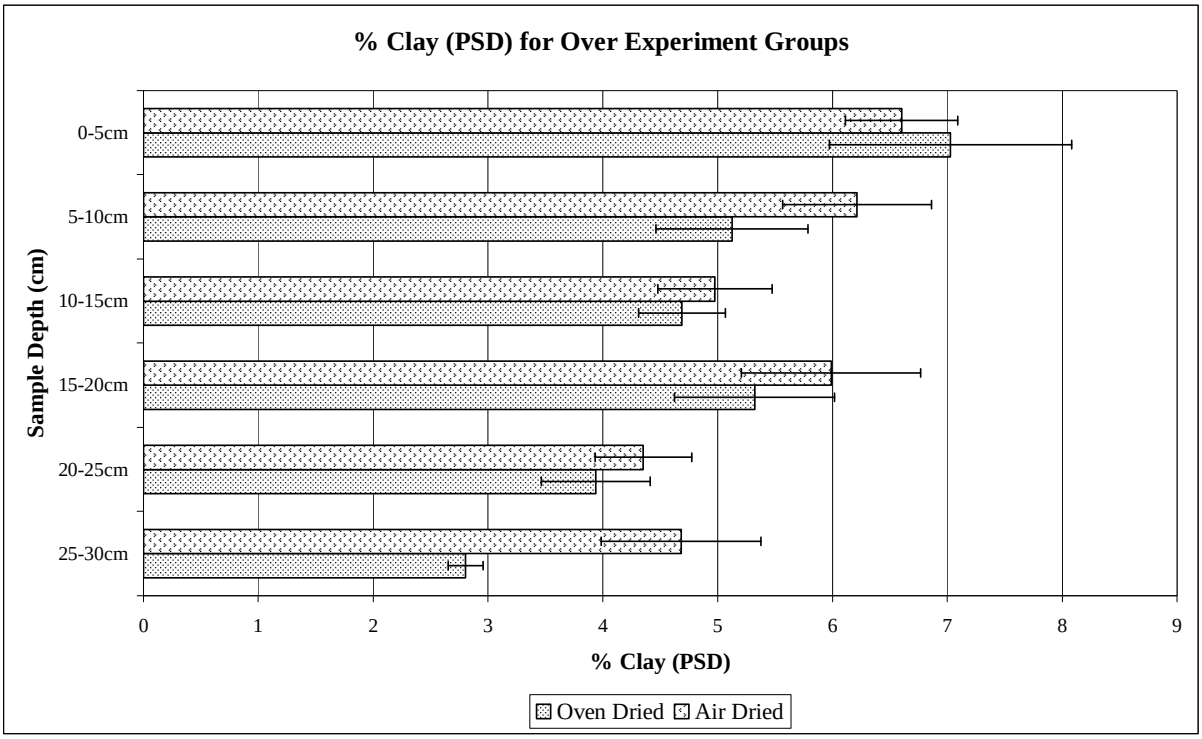


Figure 4.5. Mean and standard error for %Clay (PSD) to determine seasonal variation for both the oven dried and air dried experiment groups.

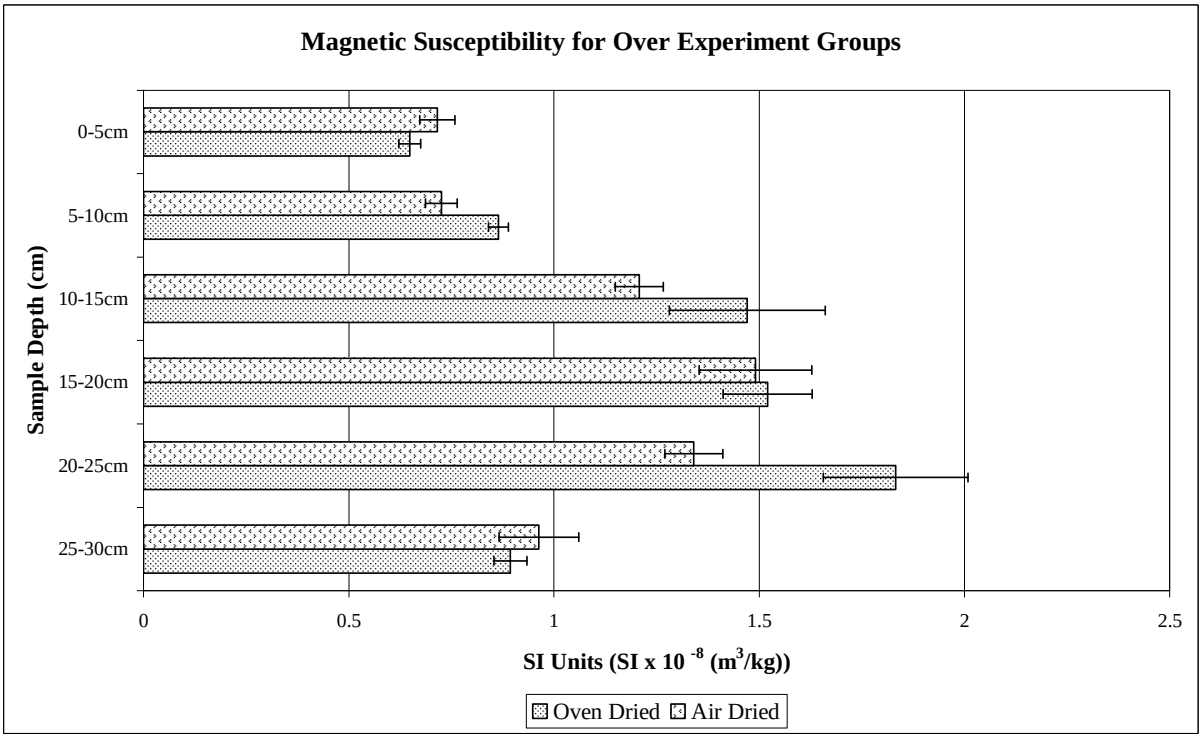


Figure 4.6. Mean and standard error for magnetic susceptibility to determine seasonal variation for both the oven dried and air dried experiment groups.

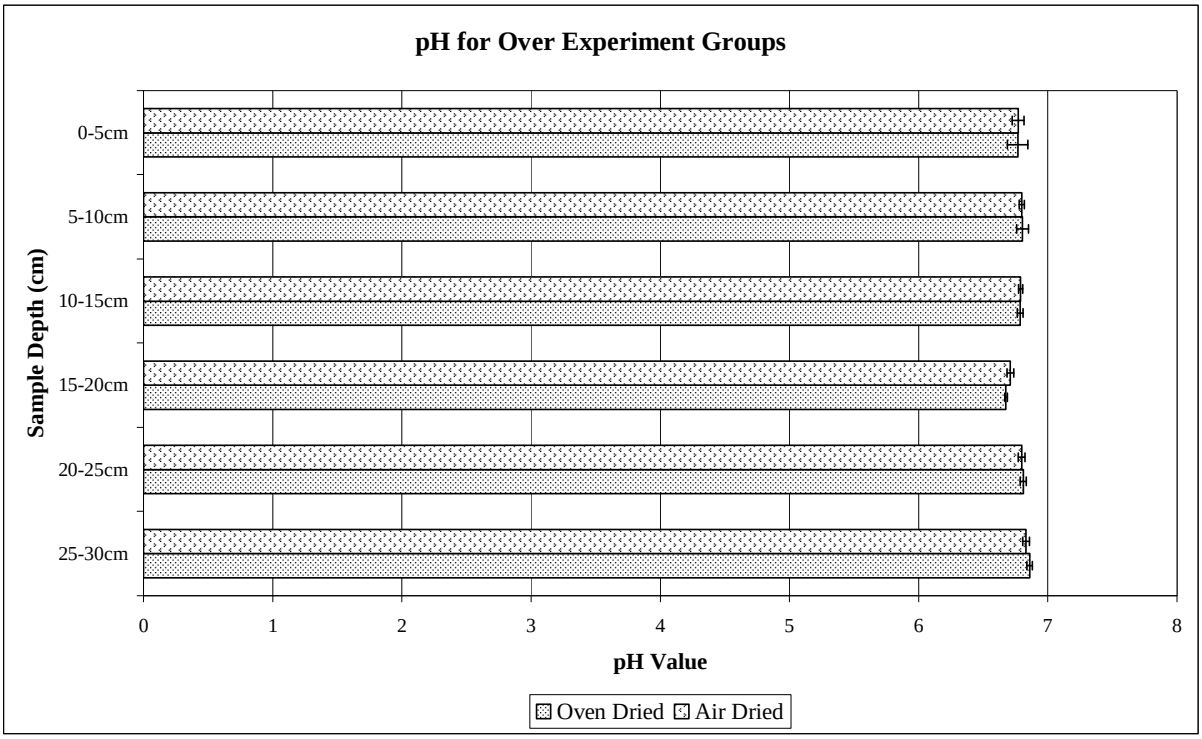


Figure 4.7. Mean and standard error for pH to determine seasonal variation for both the oven dried and air dried experiment groups.

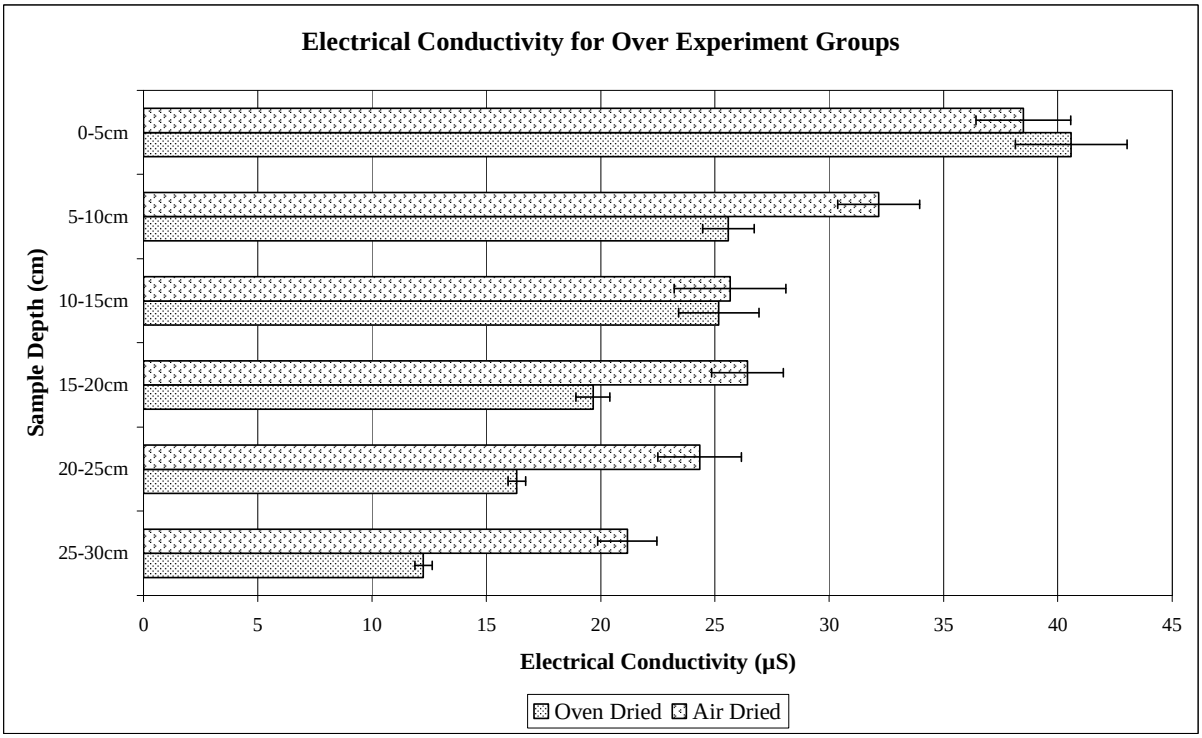


Figure 4.8. Mean and standard error for electrical conductivity to determine seasonal variation for both the oven dried and air dried experiment groups.

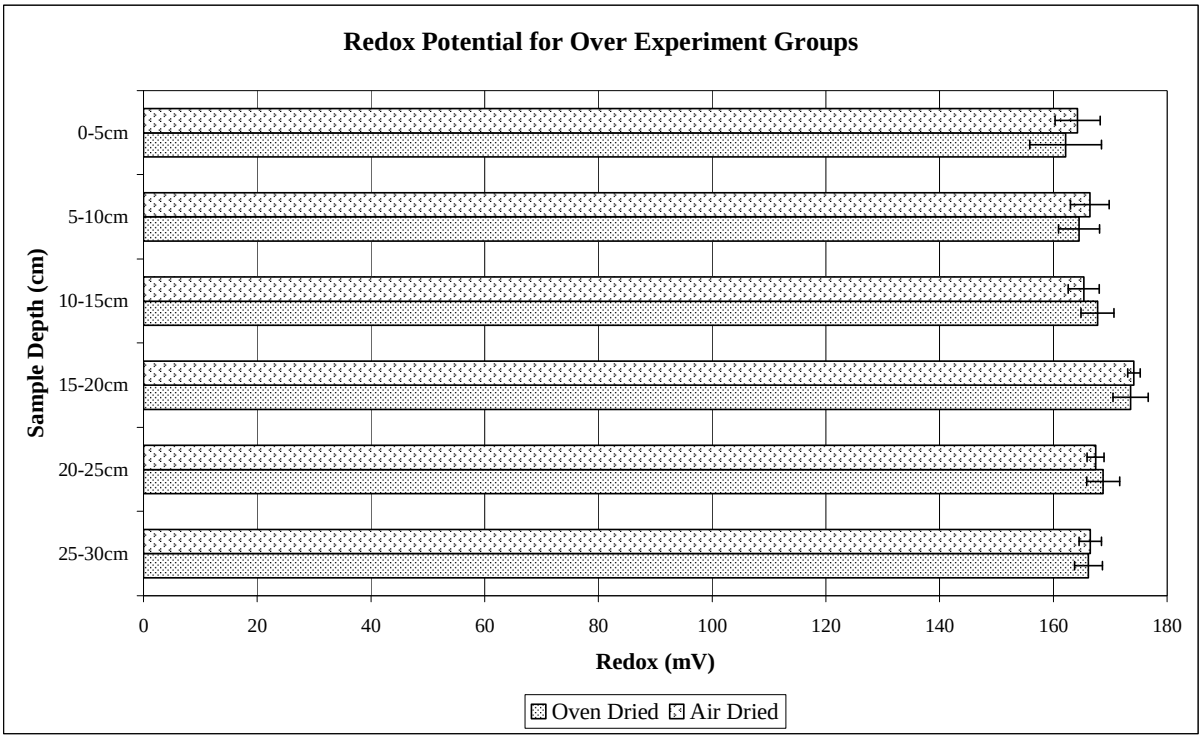


Figure 4.9. Mean and standard error for redox potential to determine seasonal variation for both the oven dried and air dried experiment groups.

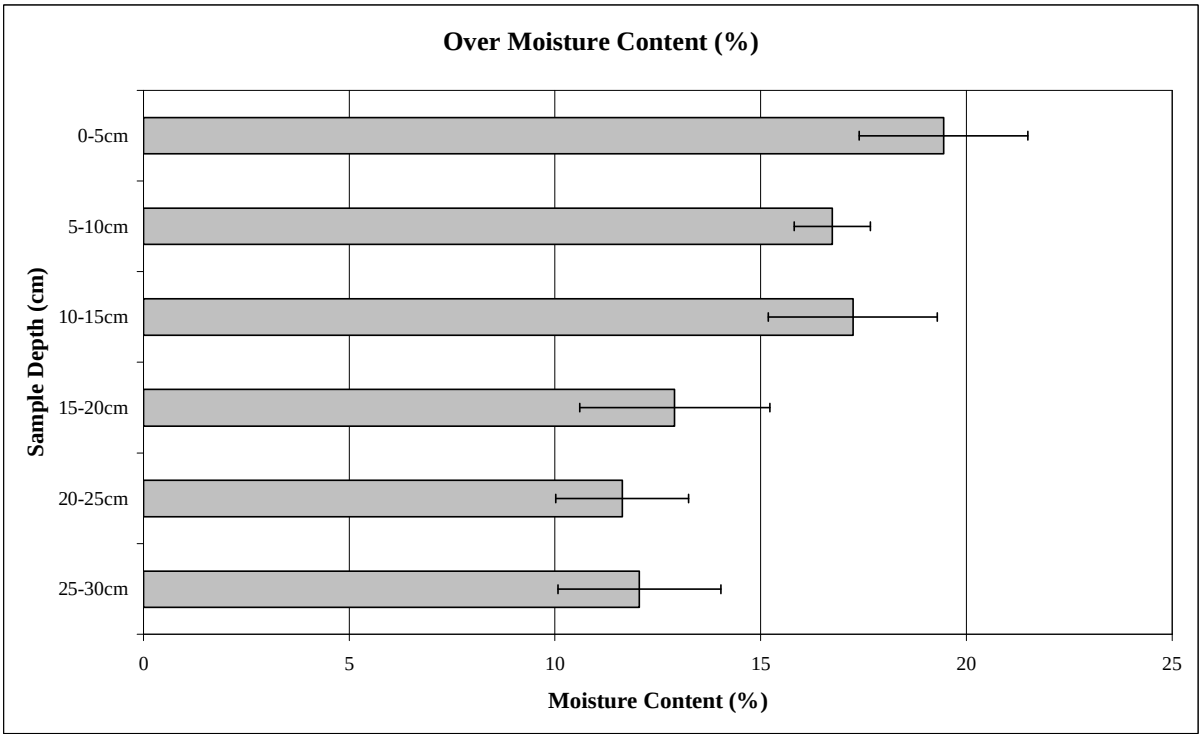


Figure 4.10. Mean and standard error to determine seasonal variation for the moisture content taken prior to the oxidation experiments.

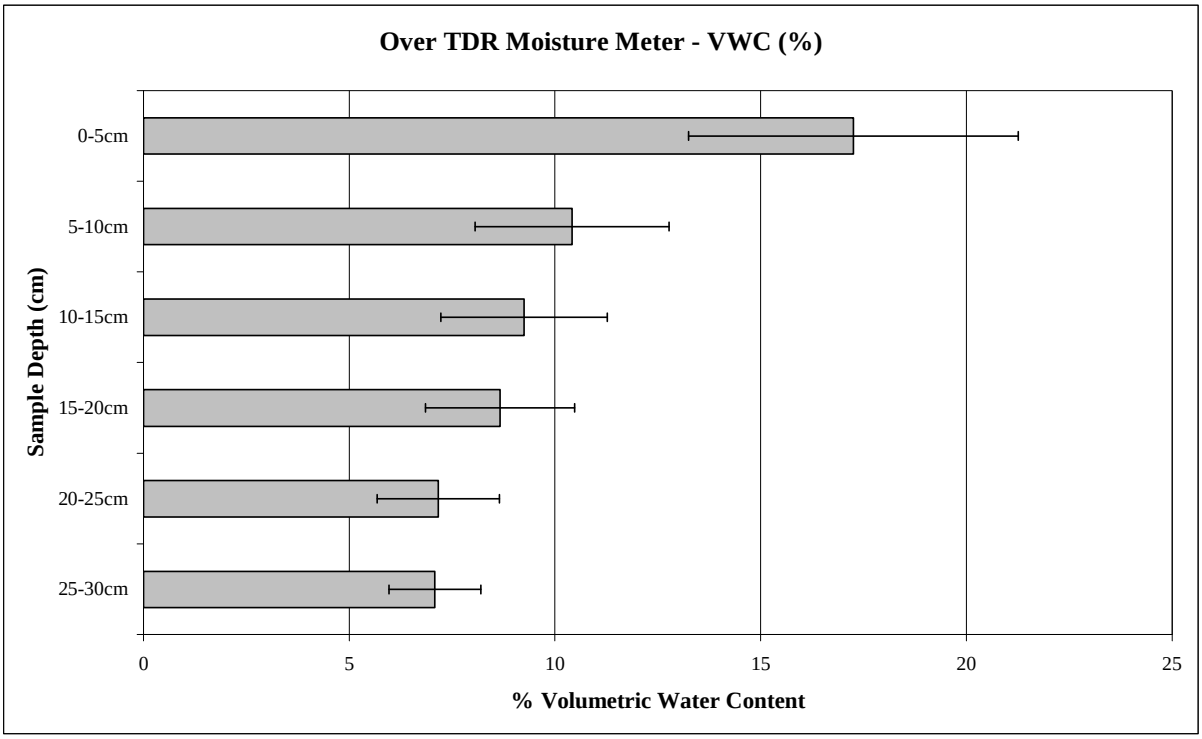


Figure 4.11. Mean and standard error to determine seasonal variation in soil moisture content for the in-field measurements taken prior to sampling.

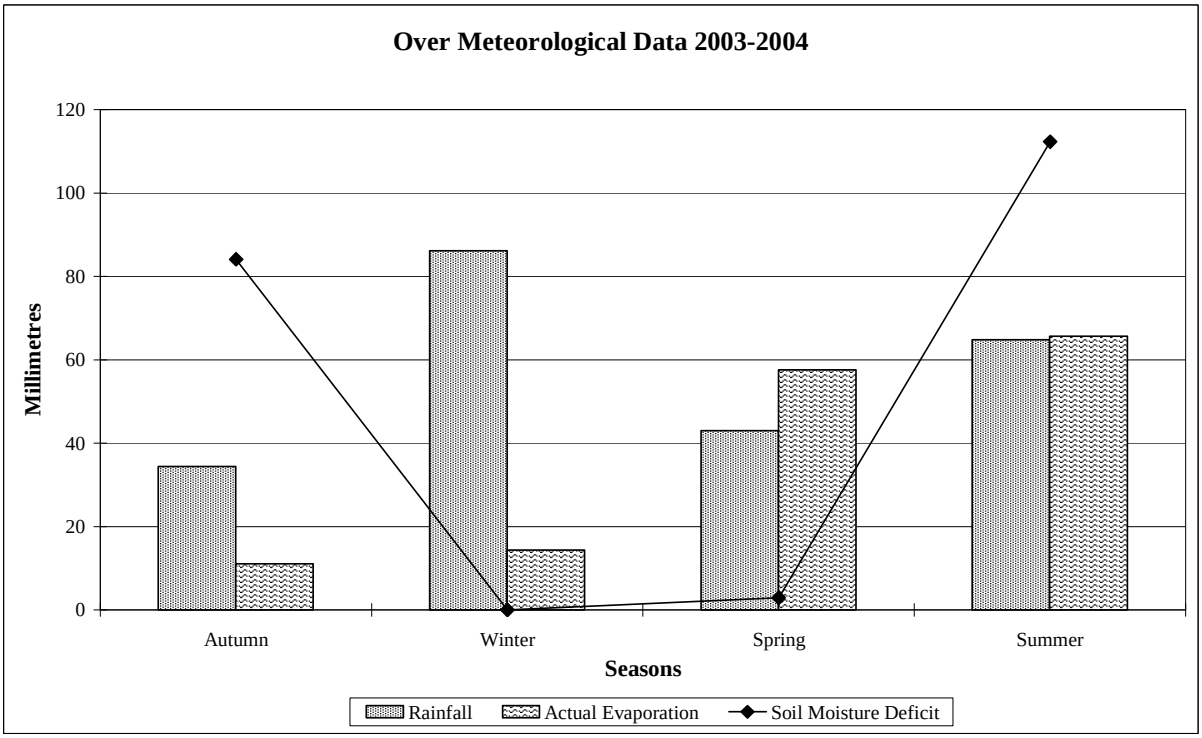


Figure 4.12. Rainfall, actual evaporation and soil moisture deficit for Over from autumn 2003 to summer 2004 (October 2003, January, April and July, 2004). This data is based on a wheat crop (data supplied by MORECS).

The results from the moisture content (figure 4.10), which is the percentage of moisture in the soil prior to the oxidation experiments, and VWC from the in-field TDR moisture meter readings (figure 4.11) show more variation between seasons than the other bulk analyses data. This is expected as variation in rainfall and evaporation records for the collection seasons show great variability with particularly dry seasons in autumn 2003 (which followed one of the driest summers on record in the UK) and summer 2004 (figure 4.12). The meteorological data and soil water conditions presented for Over are based on a wheat crop. The crops are rotated between wheat and rape seed; 2 years of wheat followed by 1 year of rape seed.

4.2.1.2 Correlation Coefficients and Relationships between Variables

As the data for both experiment groups at Over are normally distributed (tables 4.1 and 4.2), Pearson's correlation coefficient was used to highlight relationships between the different analytical variables (Field 2005). Although relationships between variables were expected, the direction of the relationships was not predicted; therefore, a two-tailed significance test was used (*ibid*). These results are presented in tables 4.3 and 4.4 below.

Table 4.3. Pearson correlation for all bulk analyses results for the Over oven experiment group. Significant correlations are highlighted.

Correlations for Over Oven Dried Experiment Group

		Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox Potential (mV)	Bulk Density (%)	Volumetric Water Content (%)
Fe (ppm)	Pearson Correlation	1	.457*	.151	-.121	-.237	-.185	-.092	-.226	.021	-.187	-.013
	Sig. (2-tailed)		.025	.481	.574	.264	.388	.668	.289	.922	.380	.950
	N	24	24	24	24	24	24	24	24	24	24	24
Mn (ppm)	Pearson Correlation	.457*	1	-.261	-.033	.290	.188	.297	.561**	-.597**	.274	.478*
	Sig. (2-tailed)	.025		.219	.879	.169	.378	.159	.004	.002	.194	.018
	N	24	24	24	24	24	24	24	24	24	24	24
Magnetic Susceptibility (SI Units)	Pearson Correlation	.151	-.261	1	-.031	-.271	-.223	-.218	-.347	.275	.036	-.054
	Sig. (2-tailed)	.481	.219		.887	.201	.295	.307	.096	.194	.867	.804
	N	24	24	24	24	24	24	24	24	24	24	24
% Clay (PSD)	Pearson Correlation	-.121	-.033	-.031	1	.598**	.724**	-.066	.505*	.077	-.078	-.379
	Sig. (2-tailed)	.574	.879	.887		.002	.000	.759	.012	.721	.716	.068
	N	24	24	24	24	24	24	24	24	24	24	24
% Water (LOI)	Pearson Correlation	-.237	.290	-.271	.598**	1	.940**	-.123	.874**	-.039	.302	.225
	Sig. (2-tailed)	.264	.169	.201	.002		.000	.568	.000	.855	.152	.291
	N	24	24	24	24	24	24	24	24	24	24	24
% Organic Matter (LOI)	Pearson Correlation	-.185	.188	-.223	.724**	.940**	1	-.222	.787**	.094	.244	.098
	Sig. (2-tailed)	.388	.378	.295	.000	.000		.297	.000	.663	.251	.650
	N	24	24	24	24	24	24	24	24	24	24	24
pH Value	Pearson Correlation	-.092	.297	-.218	-.066	-.123	-.222	1	.186	-.744**	-.165	-.189
	Sig. (2-tailed)	.668	.159	.307	.759	.568	.297		.385	.000	.440	.376
	N	24	24	24	24	24	24	24	24	24	24	24
Electrical Conductivity (µS)	Pearson Correlation	-.226	.561**	-.347	.505*	.874**	.787**	.186	1	-.409*	.396	.336
	Sig. (2-tailed)	.289	.004	.096	.012	.000	.000	.385		.047	.055	.109
	N	24	24	24	24	24	24	24	24	24	24	24
Redox Potential (mV)	Pearson Correlation	.021	-.597**	.275	.077	-.039	.094	-.744**	-.409*	1	-.251	-.333
	Sig. (2-tailed)	.922	.002	.194	.721	.855	.663	.000	.047		.237	.112
	N	24	24	24	24	24	24	24	24	24	24	24
Bulk Density (%)	Pearson Correlation	-.187	.274	.036	-.078	.302	.244	-.165	.396	-.251	1	.755**
	Sig. (2-tailed)	.380	.194	.867	.716	.152	.251	.440	.055	.237		.000
	N	24	24	24	24	24	24	24	24	24	24	24
Volumetric Water Content (%)	Pearson Correlation	-.013	.478*	-.054	-.379	.225	.098	-.189	.336	-.333	.755**	1
	Sig. (2-tailed)	.950	.018	.804	.068	.291	.650	.376	.109	.112	.000	
	N	24	24	24	24	24	24	24	24	24	24	24

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

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

Correlations with significance levels of $p<.05$ and $p<.01$ are marked by asterisks in each of the correlation tables. I will first discuss the correlations for the oven dried experiment group, followed by the air dried experiment group for Over.

In the oven dried experiment group (table 4.3) there are significant relationships between Fe and Mn (r = .457, $p<.05$), Mn and EC (r = .561, $p<.01$), Mn and redox (r = -.597, $p<.01$), and Mn and VWC (r = .478, $p<.05$). The correlation between Mn and Fe is expected as these minerals are often found together and behave in similar ways in the soil environment (Limbrey 1975; Sparks 1996). In light of this, a relationship between Mn and redox is also likely as redox processes affect the chemistry and deposition of Mn. A relationship between Mn and VWC could be used to argue for the movement of Mn with water in the soil profile. With correlations between Mn and Fe, redox and VWC, one could argue these relationships fit in with the movement of Mn, and in an indirect way, the movement of Fe in solution via redox processes. The relationship between Mn and EC remains unclear at this stage.

There are significant relationships between %Clay and %Water (r = .598, $p<.01$), %Clay and %OM (r = .724, $p<.0001$), and %Clay and EC (r = .505, $p<.05$). The relationship between %Clay and %Water is reasonable with Over being a free draining soil; the small amount of clay that is present is likely to hold moisture and illuviation of clay via water movement in the soil profile is possible, and is confirmed by the micromorphological analyses below. The correlation between %Clay and %OM suggests that the OM present in the soil may be associated with clay, which is confirmed by the presence of fine organic punctuations identified in the micromorphological analyses. Finally, the relationship between %Clay and EC is expected as EC is known to be influenced by soil type (Carroll and Oliver 2005) and as clay holds moisture better than sand, and EC measures soluble salts, it is likely that any soluble salts within the soil will be held in the less permeable part of the soil fabric, i.e. clay. %Water and %OM also have significant relationships with EC, r = .874, $p<.0001$ and r = .787, $p<.0001$, respectively, suggesting that along with the clay component of the soil, the OM holds any remaining moisture (Carroll and Oliver 2005). Further, figures 4.3, 4.4 and 4.5 show there is less than 2% water, less than 3% OM and less than 9% clay, respectively, in the soil at Over. Correspondingly, the EC readings are very low (figure 4.8), suggesting the soil profile has undergone leaching, which may have been exacerbated by water abstraction taking place in the vicinity of the site (see section 2.11.1).

There are significant relationships between pH and redox (r = -.744, p<.0001) and EC and redox (r = -.409, p<.05). The correlation between pH and redox has been studied in the literature and pH is known to influence redox conditions in the soil (Patrick *et al.* 1996). The negative correlation suggests that the lower the pH, or the more acidic the soil is, the higher the potential for redox processes to take place, a correlation which is supported by the literature (Patrick *et al.* 1996; Trolard and Bourrié 1999). The relationship between redox and EC is unclear but may reflect the role of redox processes in the leaching of the available soluble salts in the soil, which are measured by EC. That is, the negative relationship suggests that the higher the potential for redox processes, the lower the EC will be due to leaching via redox processes. As redox processes can be the direct result of a fluctuating groundwater table and groundwater is known to have high EC, the rapid lowering of the groundwater table at Over (via water abstraction) would result in the loss of soluble salts, and thus low EC values (Caple and Dungworth 1997; Welch and Thomas 1998).

In the Over air dried experiment group (table 4.4) there are significant relationships between Fe and Mn (r = .655, p<.001), Fe and %Water (r = -.482, p<.05), Fe and %OM (r = -.643, p<.001), and Fe and EC (r = -.457, p<.05). The coupling of Fe and Mn is expected as discussed above. The negative correlations between Fe and %Water and Fe and %OM suggest that the iron measured is present in ferric form, as there is little water present for the iron to be in its soluble ferrous form, and the OM component is unlikely to be a contributing factor to the total Fe measured due to the low quantity of OM present. Again, the low proportions of OM (figure 4.4) and water (figure 4.3) in the soil relative to the high amounts of Fe (figure 4.1) are a reflection on the hydrological environment of the site, which represents the leaching of soil nutrients with the rapid lowering of the groundwater table. This is also evident in the micromorphological analyses. The relationship between Fe and EC remains unclear, although the negative correlation reflects the quantities recorded for each variable, i.e. high quantity of Fe (figure 4.1) and low EC values (figure 4.8). The low EC values support the loss of soluble salts in the soil as a result of leaching via water abstraction in the vicinity of the site.

EC and %OM (r = .600, p<.01) are correlated along with %OM and %Water (r = .907, p<.0001), and %OM and %Clay (r = .444, p<.05). Similar to the oven dried experiment group, the relationships between EC and %OM and %Water and %OM suggest that the water that is present in the air dried experiment group is most likely trapped in the OM in the soil. The relationship between %OM and %Clay is similar to the oven dried experiment group and suggests an association of OM with clay, which is confirmed by the presence of fine

Table 4.4. Pearson correlation for all bulk analyses results for the Over air dried experiment group. Significant correlations are highlighted.

Correlations for Over Air Dried Experiment Group

		Fe (ppm)	Mn (ppm)	Magnetic Susceptibilty (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox Potential (mV)	Bulk Density (%)	Volumetric Water Content (%)
Fe (ppm)	Pearson Correlation	1	.655**	.233	-.191	-.482*	-.643**	-.029	-.457*	.049	-.062	.154
	Sig. (2-tailed)		.001	.272	.371	.017	.001	.894	.025	.821	.772	.472
	N	24	24	24	24	24	24	24	24	24	24	24
Mn (ppm)	Pearson Correlation	.655**	1	-.132	-.250	-.060	-.200	.070	-.068	.019	.199	.388
	Sig. (2-tailed)	.001		.538	.240	.780	.349	.747	.752	.931	.352	.061
	N	24	24	24	24	24	24	24	24	24	24	24
Magnetic Susceptibilty (SI Units)	Pearson Correlation	.233	-.132	1	.109	-.304	-.301	-.103	-.321	-.043	-.240	-.227
	Sig. (2-tailed)	.272	.538		.611	.148	.153	.633	.126	.842	.259	.287
	N	24	24	24	24	24	24	24	24	24	24	24
% Clay (PSD)	Pearson Correlation	-.191	-.250	.109	1	.286	.444*	-.315	.085	-.145	.217	-.063
	Sig. (2-tailed)	.371	.240	.611		.176	.030	.134	.691	.498	.309	.770
	N	24	24	24	24	24	24	24	24	24	24	24
% Water (LOI)	Pearson Correlation	-.482*	-.060	-.304	.286	1	.907**	-.422*	.377	.236	.529**	.368
	Sig. (2-tailed)	.017	.780	.148	.176		.000	.040	.069	.267	.008	.077
	N	24	24	24	24	24	24	24	24	24	24	24
% Organic Matter (LOI)	Pearson Correlation	-.643**	-.200	-.301	.444*	.907**	1	-.247	.600**	-.044	.360	.188
	Sig. (2-tailed)	.001	.349	.153	.030	.000		.245	.002	.839	.084	.379
	N	24	24	24	24	24	24	24	24	24	24	24
pH Value	Pearson Correlation	-.029	.070	-.103	-.315	-.422*	-.247	1	.127	-.695**	-.626**	-.491*
	Sig. (2-tailed)	.894	.747	.633	.134	.040	.245		.555	.000	.001	.015
	N	24	24	24	24	24	24	24	24	24	24	24
Electrical Conductivity (µS)	Pearson Correlation	-.457*	-.068	-.321	.085	.377	.600**	.127	1	-.260	-.024	.045
	Sig. (2-tailed)	.025	.752	.126	.691	.069	.002	.555		.220	.912	.835
	N	24	24	24	24	24	24	24	24	24	24	24
Redox Potential (mV)	Pearson Correlation	.049	.019	-.043	-.145	.236	-.044	-.695**	-.260	1	.342	.200
	Sig. (2-tailed)	.821	.931	.842	.498	.267	.839	.000	.220		.102	.348
	N	24	24	24	24	24	24	24	24	24	24	24
Bulk Density (%)	Pearson Correlation	-.062	.199	-.240	.217	.529**	.360	-.626**	-.024	.342	1	.755**
	Sig. (2-tailed)	.772	.352	.259	.309	.008	.084	.001	.912	.102		.000
	N	24	24	24	24	24	24	24	24	24	24	24
Volumetric Water Content (%)	Pearson Correlation	.154	.388	-.227	-.063	.368	.188	-.491*	.045	.200	.755**	1
	Sig. (2-tailed)	.472	.061	.287	.770	.077	.379	.015	.835	.348	.000	
	N	24	24	24	24	24	24	24	24	24	24	24

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

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

amorphous organic matter and punctuations identified from the micromorphological analyses. Further similarities with the oven dried group are the low quantities of clay (figure 4.5), OM (figure 4.4) and water (figure 4.3) in the air dried experiment group, along with the low EC readings (figure 4.8); suggesting leaching has taken place in the soil profile.

There are several correlations with pH, including pH and redox ($r = -.695$, $p<.0001$), pH and %Water ($r = -.422$, $p<.05$), pH and moisture content ($r = -.626$, $p<.001$), and pH and VWC ($r = -.491$, $p<.05$). The relationship between pH and redox is already established as a causal one. The negative correlations between pH and %Water, pH and moisture content and pH and VWC reflect the physical environment at Over with a mean pH of 6.8, a watertable that is at least 5m below the ground surface and highly permeable sandy soils, which are inefficient at retaining moisture.

The positive correlation between %Water and moisture content ($r = .529$, $p<.01$) suggests that the air dried experiment group retained more moisture in the soil than the oven dried experiment group, which showed no correlation between these two variables. However, the distribution of moisture retained in the soils from the air dried group could simply resemble more closely the pattern of distribution for moisture content than the oven dried experiment group (figures 4.3 and 4.10).

Finally, the correlation between moisture content and VWC ($r = .755$, $p<.0001$) is present in tables 4.3 and 4.4. The correlations in these tables are identical as they were taken as a control for the moisture in the soil prior to the drying out experiments. The strong positive correlation between these variables confirms the accuracy of both methods: moisture content is a measure of soil moisture before drying out, and is as close to in-field moisture levels as possible in a laboratory environment, and VWC is a direct in-field reading of the soil moisture content at Over.

Only one variable, MS, has no correlations for both the oven dried experiment group and the air dried experiment group. Due to the high quantities of Fe and Mn present in the soil at Over, an equally high reading for MS is expected. However, the MS readings for Over are extremely low (figure 4.6), which suggests that the soil at Over has naturally low magnetic susceptibility. Further, due to the low quantity of organic material in the soil at Over, the nutrients often associated with organic material, which may have magnetic properties, are not

present in significant quantities (appendix G, table G-1) (Courtney and Trudgill 1976, 63; Trudgill 1977, 25).

4.2.2 Soil Micromorphology

Soil micromorphological analyses were carried out for each experiment group: oven dried, air dried and control, with particular focus on microstructure, relative porosity, iron oxide deposition, and organic material (appendix F). The descriptions follow Bullock *et al.* (1985) and Stoops (2003) and the coarse-fine limit for the soils at Over is set at 20µm. I will first provide a brief description of the soil microstructure and porosity, followed by more detail on iron oxide deposition and organic material.

4.2.2.1 Microstructure and Porosity

The soil at Over is a fine sandy soil with a pellicular to bridged grain microstructure, which is dominantly sand-sized grains with most grains coated by fine material such as clay, and with some iron-rich silty clay bridged between the sand grains. This is further demonstrated by its chitonic to concave gefuric related distribution and coarse-fine ratio of 5:1. The little fine material present in the soil is in the form of silty clay coatings of grains and in some cases, of packing voids with zones of randomly oriented silty clay striations. The soil porosity shows little seasonal variation or variation between experiment groups, which is expected given the dominant sandy component of the soil (figure 4.13).

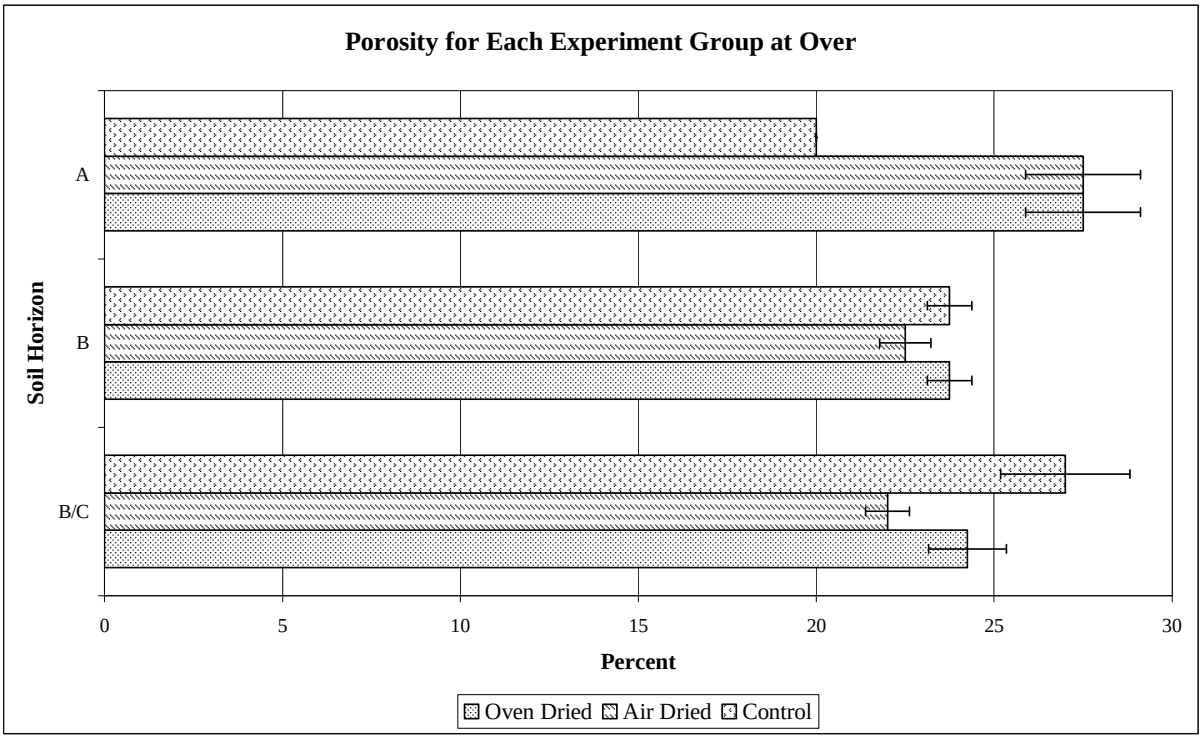


Figure 4.13. Mean porosity (%) and seasonal variation (error bars) for the soils at Over for all experiment groups.

4.2.2.2 Iron Oxide Deposition

The different types of iron oxide deposition present in the soils at Over include nodules, staining, coatings, replacement and micro-pans. The iron micro-pans were present in only the autumn sample collection: two in the oven dried samples and three in the control group (appendix F). These micro-pans are likely to have formed around roots and rootlets within the soil and are the result of decaying organic material. There are two cases of iron replacement of organic material in the October samples, which are associated with the iron micro-pans. There is also some iron replacement in the spring control samples. The presence of iron replacement in the samples at Over is expected as this process is the result of repeated redox cycles, which occur during fluctuations of the groundwater table. Although the groundwater table is presently 5m below the ground surface, prior to water abstraction the watertable was recorded to be about 1.2m to 1.5m below the surface, and therefore, seasonal fluctuations of this higher level of groundwater resulted in the iron replacement of organic material.

Iron coatings were also recorded at Over, and are the result of illuviation of iron-rich clay down through the soil profile. There is some variation between experiment groups, more so in the lower horizons (figure 4.14). However, the oxidation experiments are unlikely to affect

the process by which coatings occur, i.e. illuviation, and this variation is more likely to be representative of the natural variation within the soil at Over. There also appears to be substantial seasonal variation, which may be attributed to the variable rainfall at Over as the clay is illuviated through the soil profile via precipitation, colloidal suspension, and the subsequent capillary action of the soil.

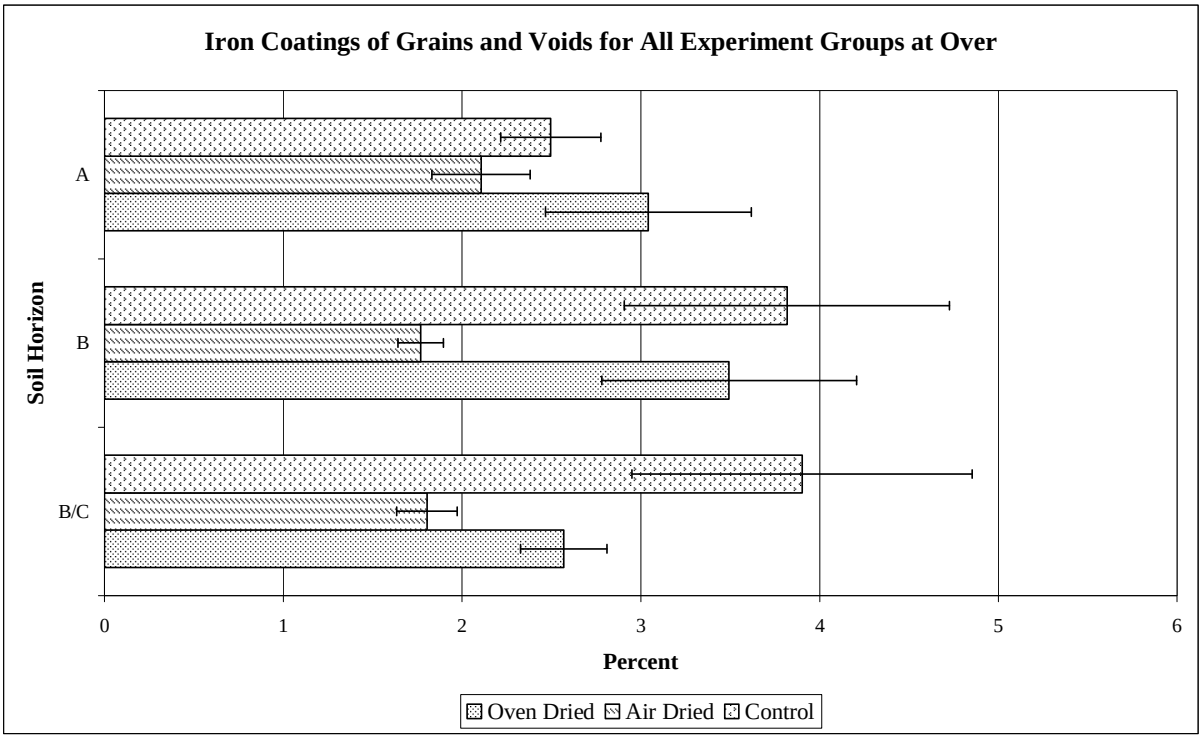


Figure 4.14. Mean percentage of coatings and seasonal variation (error bars) for all experiment groups at Over.

Two types of iron oxide deposition that are likely to be affected by the oxidation experiments are iron staining and iron nodules; the former the result of slow oxidation (air dried group) and the latter the result of rapid oxidation (oven dried group). The graphs in figures 4.15 to 4.17 reflect this pattern of iron oxide deposition.

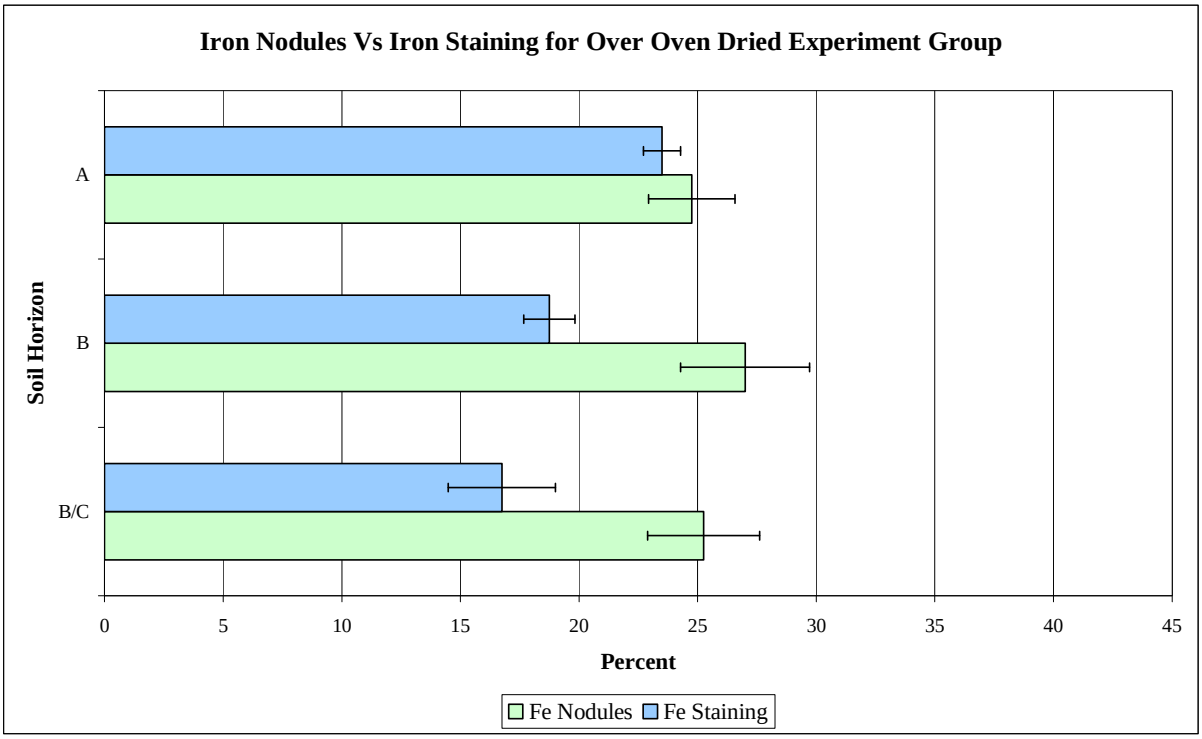


Figure 4.15. Mean percentage of iron nodules and iron staining, and the seasonal variation (error bars) for the oven dried experiment group at Over.

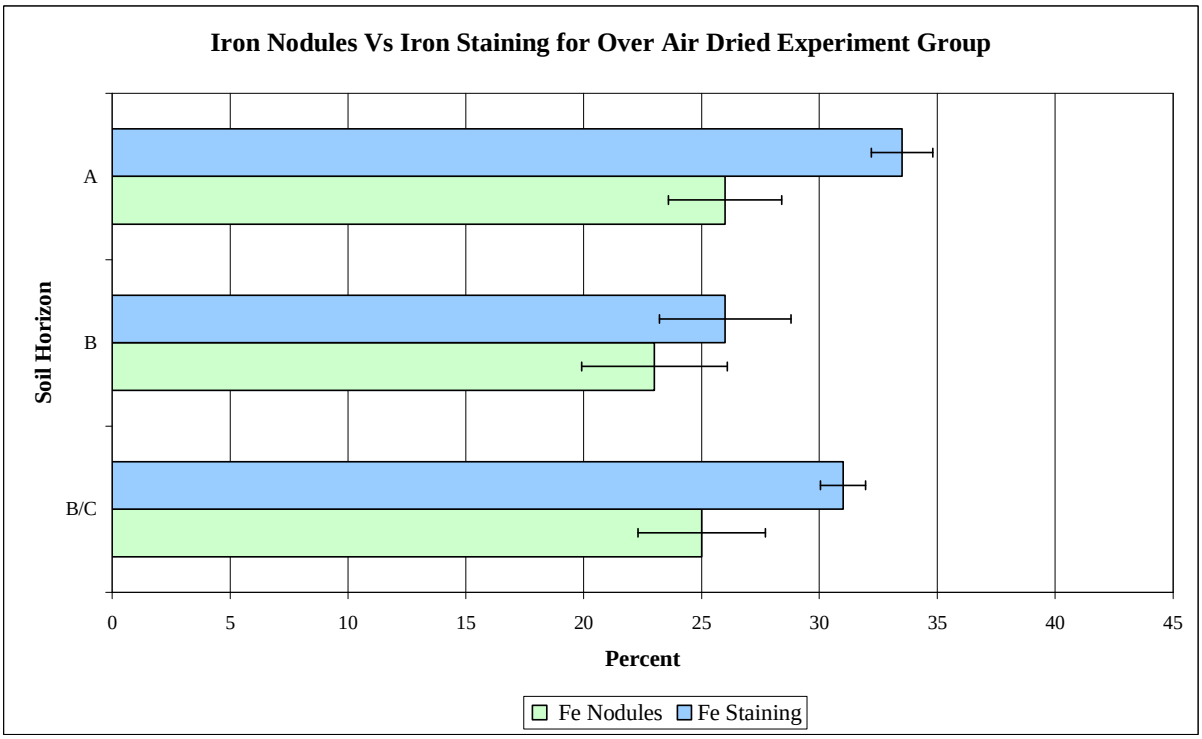


Figure 4.16. Mean percentage of iron nodules and iron staining, and the seasonal variation (error bars) for the air dried experiment group at Over.

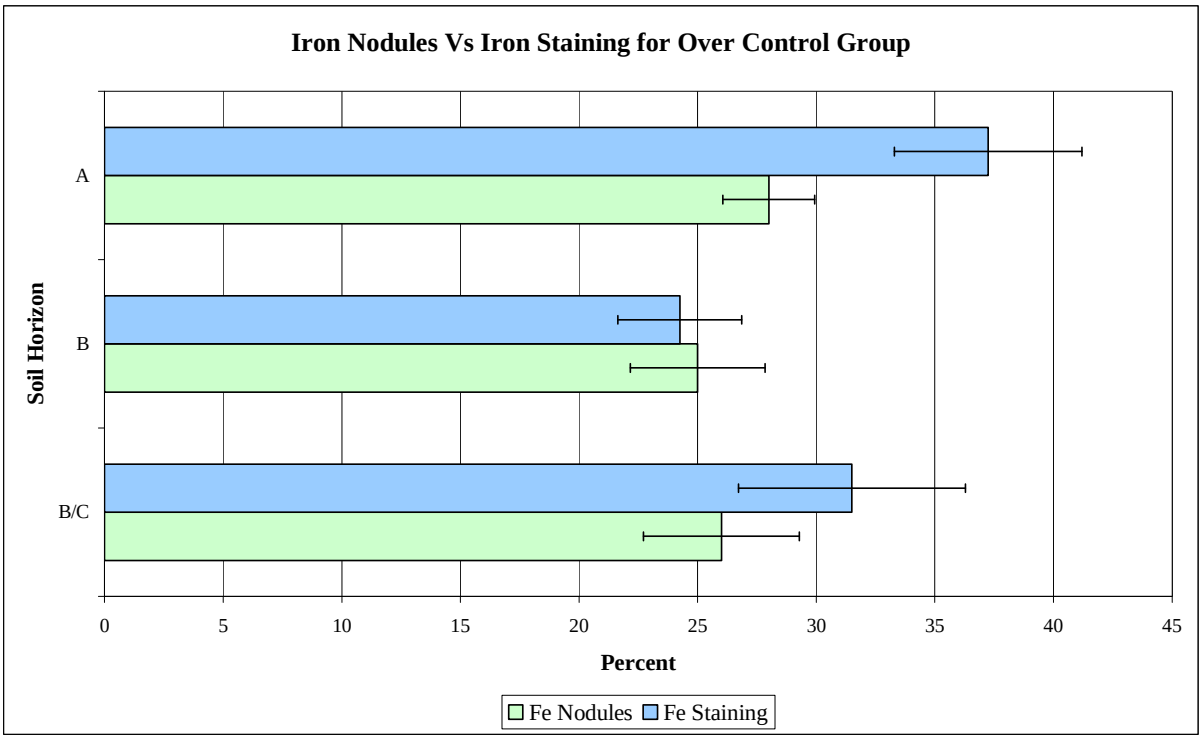


Figure 4.17. Mean percentage of iron nodules and iron staining, and the seasonal variation (error bars) for the control group at Over.

For both the oven dried experiment group and the air dried experiment group, seasonal variation is minimal and the distributions between iron nodules and iron staining suggest that the sensitivity of iron, its transformation from ferrous to ferric iron, and its deposition pattern are affected by the rate of oxidation. The results for the control group show that iron staining dominates the upper and lower horizons with more seasonal variability than the oxidation groups. This increase in staining and in seasonal variability may be an artefact of sample processing. Although acetone replacement was used to ensure that the samples remained as close to their *in situ* condition as possible with regard to oxidation, during the course of processing other thin sections under similar conditions, it has been noticed that some degree of oxidation does occur. For example, whilst dehydrating a sample from anaerobic conditions using acetone replacement prior to impregnation and thin sectioning, at some point during the process, the sample was exposed to oxygen and the ferrous iron within the sample oxidised leaving a red-brown streak through the section, which was not there prior to impregnation.

4.2.2.3 Organic Material

Table 4.5 presents the percentage frequencies and preservation state for the organic material identified through soil micromorphological analysis. In addition to the frequencies and the

state of preservation of the organic material, the size range for celled material, and whether or not the organic material is associated with iron oxide, is also noted (appendix F).

There is very little organic material in the soil at Over, with the majority of organics in the form of fine organic punctuations (<1µm) and amorphous organic material (>1µm). There are a few instances of celled material present, of which the majority are in a state of decomposition. This is noted by their numerical value, which corresponds to the colour of the organic material: 1 being the least decomposed and 5 being the most decomposed. This range of decomposition in relation to colour has been studied by Babel (1981), who suggests that the process of blackening of organic material is indicative of its progressive decomposition. The charcoal is predominantly less than 100µm (5-10%) with less than 2% charcoal being greater than 100µm. Overall, there is little seasonal variation with the exception of autumn, which has celled organic material present in the oven dried and control groups. This also corresponds with the presence of iron micro-pans in these samples, which provide a barrier against the leaching of the organic material from the soil.

While it is obvious that the preservation of organic material is poor in each experiment group, the minor differences that are present cannot confidently be associated with the effects of the oxidation experiments. It is more likely that the rapid lowering of the groundwater table ahead of gravel extraction in the vicinity of the site has caused the significant loss of organic material within the natural soil profile. This water abstraction has caused the nutrients present in the soil to be leached out (and is evident from the bulk analyses discussed above). Where some organic material remains, it is associated with iron micro-pans, which have created an impermeable barrier preventing the leaching of this material from the soil.

Table 4.5. Percentage of organic material for Over identified through micromorphological analysis.

Sample Number		Soil Horizon	Amorphous		Charcoal		Celled			Plectenchyma (Fungi)	Pollen
			Punctuations	Matter	< 100um	> 100um	Lignified	Parenchymatic	Phlobaphene		
October 2003	1.1	A	■■■	■■	■■					■ 5	
	1.2	B	■■	■■				■ 4	■ 3		
	1.3	B/C	■	■	■	■					
	2.1	A	■■		■■	■					
	2.2	B	■■		■■						
	2.3	B/C	■■		■■	■					
	3.1	A	■■■	■■	■■	■	■ 1	■ 1-5		■ 3-5	
	3.2	B	■■■	■■	■	■		■ 4-5			
	3.3	B/C	■■	■■				■ 3-5	■ 3-4		
January 2004	1.1	A	■■■		■■	■					
	1.2	B	■■		■■■	■■					
	1.3	B/C	■■■		■■■	■					
	2.1	A	■■■		■■	■				■ 4-5	
	2.2	B	■■■		■■	■					
	2.3	B/C	■■■		■						
	3.1	A	■■■■		■■■	■					
	3.2	B	■■■		■■■	■					
	3.3	B/C	■■		■■■	■					
April 2004	1.1	A	■■■		■■	■					
	1.2	B	■■■		■■	■					
	1.3	B/C	■■■		■■	■					
	2.1	A	■■■		■■■	■					
	2.2	B	■■■		■■						
	2.3	B/C	■■■		■■	■					
	3.1	A	■■■		■■	■					
	3.2	B	■■■		■■■	■					
	3.3	B/C	■■■		■■	■					
July 2004	1.1	A	■■■		■■	■					
	1.2	B	■■		■■	■					
	1.3	B/C	■■		■■	■					
	2.1	A	■■■		■■■	■					
	2.2	B	■■		■■■	■					
	2.3	B/C	■■		■■	■					
	3.1	A	■■■		■■	■					
	3.2	B	■■■		■■	■					
	3.3	B/C	■■		■■	■					

Key: ■ <2%, ■■ 2-5%, ■■■ 5-10%, ■■■■ 10-20%, ■■■■■ 20-30%, ■■■■■■ 30-40%, ■■■■■■■ 40-50%, ■■■■■■■■ 50-60%, ■■■■■■■■■ 60-70%

Key to preservation of organic material: 1 = fresh; 2 = yellow; 3 = red-brown; 4 = brown; 5 = black

4.2.3 CDB for an Alluvial Brown Earth

The bulk and micromorphological data for Over revealed little variation either seasonally or between experiment groups, with the exception of iron staining and iron nodules as identified through soil micromorphology. The data showed that the soils at Over have undergone significant loss of organic material and other soil nutrients. This is most likely the result of the rapid lowering of the groundwater table ahead of gravel extraction in the vicinity of the site.

Bringing together the bulk and soil micromorphological data for the experiment groups at Over, in a way that is functional and clear as a reference guide to gauging preservation, has resulted in the formation of the comparative database (CDB). This database is represented by two graphs (figures 4.18 and 4.19), which highlight the variables that are most likely to provide the best representation of the oxidation environment within the soil.

Given the lack of significant seasonal variation for each of the bulk and micromorphological analyses, the means for each variable have been used to formulate the graphs in figures 4.18 and 4.19 in reference to their soil depth and soil horizon. For each figure, a sedimentological key is provided to represent the soil profile at the site, and the corresponding bulk and soil micromorphological results are mapped out in accordance with their context in the soil profile. Two variables from the soil micromorphological analyses have been used for these graphs: iron nodules and iron staining, as these variables prove the most informative for determining the oxidation and/or hydrological environment for an alluvial brown earth such as Over.

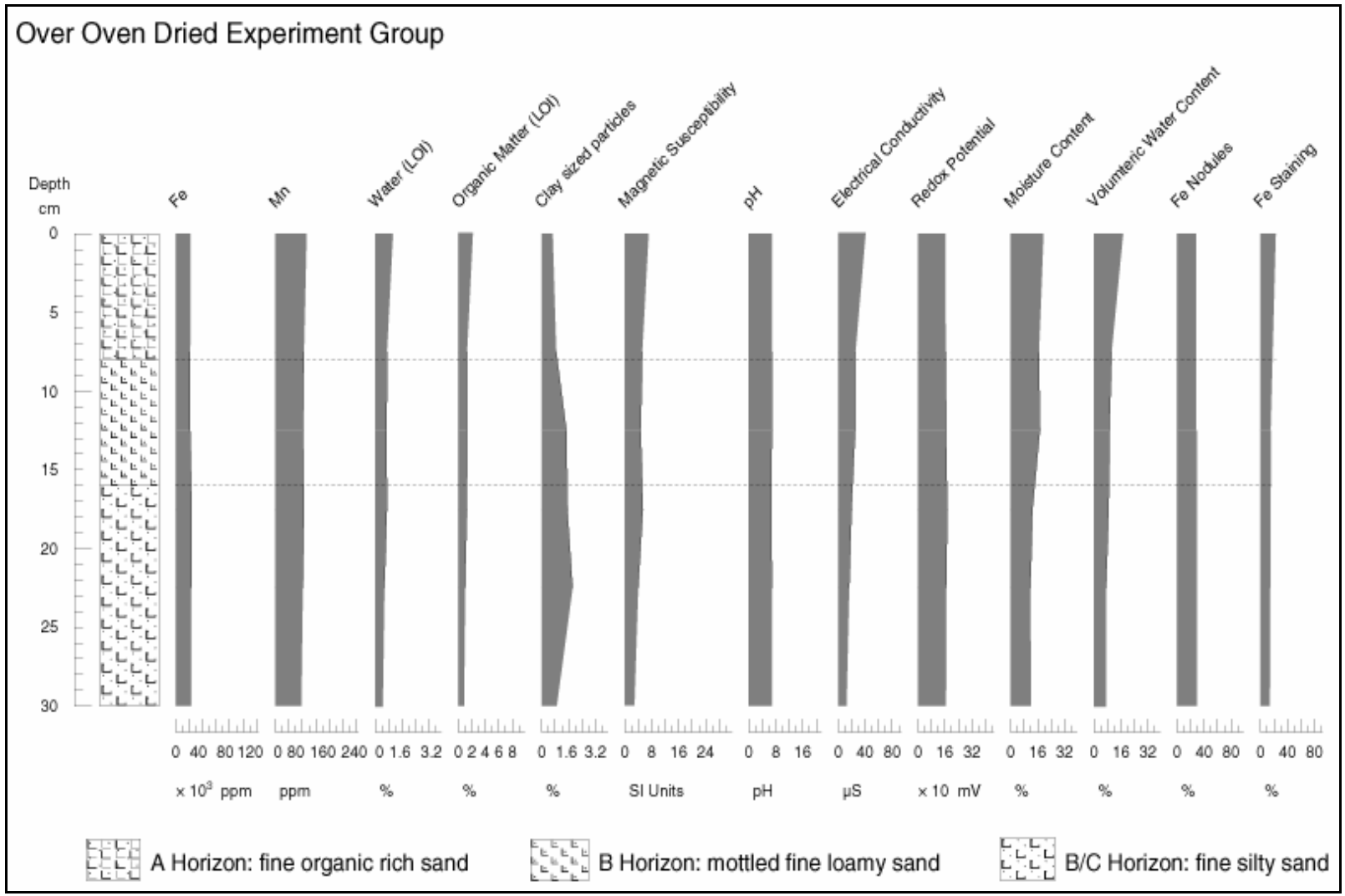


Figure 4.18. The comparative database (CDB) for the Over oven dried experiment group.

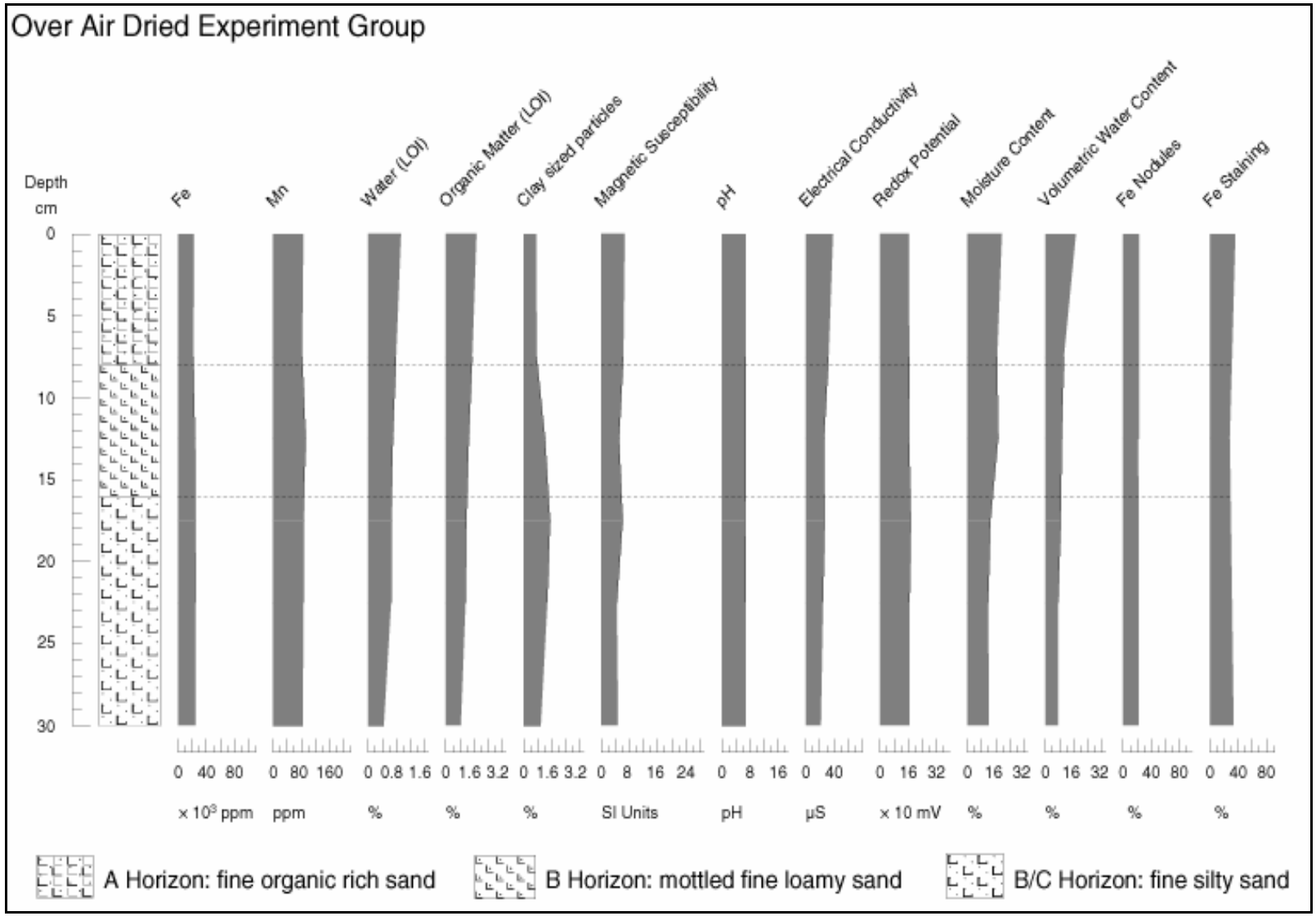


Figure 4.19. The comparative database (CDB) for the Over air dried experiment group.

While the results for the bulk analyses for both the oven dried and the air dried experiment group are very similar and do not provide any significant differences, the two micromorphological variables differ quite significantly. In the oven dried experiment group iron **nodules** dominate over iron staining, which corresponds to the effects of the **rapid** oxidation of the soil. Conversely, in the air dried experiment group iron **staining** is more predominant than iron nodules, which corresponds to the effects of **slow** oxidation of the soil. The significance of these differences and their representations of the oxidation environment for the soils provide valuable information for determining the effects these processes have on the preservation of organic material. Unfortunately, it is difficult to ascertain the direct effects the oxidation experiments had on the organic material at Over due to the hydrological changes that have occurred at the site prior to this research. The rapid reduction of the groundwater table at Over ahead of gravel extraction has affected both the quantity and quality of organic preservation. As a result, the control group used for this research is only representative of the soil profile in its present, altered state, and is not representative of the natural soil environment prior to abstraction. As discussed in previous chapters, the introduction of oxygen into an anaerobic environment is highly detrimental to all organic material. However, the rate in which oxygen is introduced can have variable effects on this deterioration; rapid oxidation proves immediately detrimental to organic material, while slow oxidation provides a delay in organic deterioration (cf. Welch and Thomas 1998), and in the case of replacement aids in the preservation of plant cellular material. However, the caveat to this scenario is repeated cycles of aerobic and anaerobic conditions typical of redox processes, which in the long term can be equally detrimental to organic material as rapid oxidation (cf. *ibid*).

4.3 WANDLEBURY

Wandlebury is a typical calcareous rendzina, on a chalk substrate, under a pastoral environment. The results of the bulk and soil micromorphological analyses (see table 3.1 in section 3.2) follow for each experiment group.

4.3.1 Bulk Analyses Data

A suite of bulk analyses were conducted on the oven dried and air dried bulk samples (see table 3.1 in section 3.2). Moisture content and VWC were recorded prior to the oxidation experiments and meteorological and soil water data were collected from MORECS. The results for each analysis for the oven dried group are presented here, followed by the results for the air dried group.

4.3.1.1 The Normal Curve and Seasonal Variation

The data for each analysis were tested for normal distribution by using a one-sampled K-S test (Field 2005). If the result is $p>.05$, then the data is deemed normally distributed. The results of this test for all the bulk analyses (oven dried group followed by air dried group) are presented in tables 4.6 and 4.7.

Table 4.6. Results of the normal distribution test for the oven dried group across all seasons. The row highlighted in yellow indicates that this group is normally distributed.

One-Sample Kolmogorov-Smirnov Test for Wandlebury Oven Dried Experiment Group

		Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox (mV)	Bulk Density (%)	Volumetric Water Content (%)
N		24	24	24	24	24	24	24	24	24	24	24
Normal Parameters[a,b]	Mean	19050.00	655.13	13.08	11.83	2.25	9.31	8.13	209.61	125.89	19.91	19.75
	Std. Deviation	1453.93	34.04	1.42	2.80	.24	1.22	.21	64.68	8.77	5.57	6.86
Most Extreme Differences	Absolute	.20	.20	.16	.15	.18	.15	.11	.19	.08	.17	.19
	Positive	.12	.18	.12	.15	.11	.13	.11	.19	.07	.10	.19
	Negative	-.20	-.20	-.16	-.14	-.18	-.15	-.10	-.09	-.08	-.17	-.13
Kolmogorov-Smirnov Z		.96	1.00	.78	.72	.87	.76	.54	.95	.41	.82	.92
Asymp. Sig. (2-tailed)		.31	.27	.58	.68	.44	.62	.94	.33	1.00	.51	.37

a. Test distribution is Normal.

b. Calculated from data.

Table 4.7. Results of the normal distribution test for the air dried group across all seasons. The value highlighted in bright blue indicates that this group is *not* normally distributed.

One-Sample Kolmogorov-Smirnov Test for Wandlebury Air Dried Experiment Group

		Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox (mV)	Bulk Density (%)	Volumetric Water Content (%)
N		24	24	24	24	24	24	24	24	24	24	24
Normal Parameters[a,b]	Mean	16983.33	598.42	12.86	12.52	2.72	9.05	8.18	174.88	130.01	19.91	19.75
	Std. Deviation	1988.81	52.91	1.70	2.87	.39	1.37	.17	28.54	10.10	5.57	6.86
Most Extreme Differences	Absolute	.32	.26	.17	.19	.16	.17	.11	.14	.16	.17	.19
	Positive	.18	.21	.07	.19	.09	.10	.11	.14	.16	.10	.19
	Negative	-.32	-.26	-.17	-.19	-.16	-.17	-.11	-.08	-.11	-.17	-.13
Kolmogorov-Smirnov Z		1.56	1.29	.82	.93	.78	.83	.52	.66	.80	.82	.92
Asymp. Sig. (2-tailed)		.02	.07	.51	.36	.57	.49	.95	.77	.55	.51	.37

a. Test distribution is Normal.

b. Calculated from data.

Data from the oven dried and air dried experiment group for Wandlebury are normally distributed as is evident from the rows highlighted in yellow, with the exception of total Fe (ICP-AES) in the air dried experiment group. In order to assess seasonal variability at Wandlebury, the means and standard errors were calculated for each bulk analysis and experiment group. The results are presented using bar graphs with error bars, as in figures 4.20 to 4.30 below.

Figures 4.20 to 4.28 present the results of each of the bulk analyses for the oven dried and the air dried experiment groups. These figures show there is little seasonal variation, as represented by the error bars, and overall, there appears to be little difference between experiment groups. This result is expected as physical properties, such as MS, pH, EC, redox and %OM, in the soil are unlikely to be affected by the oxidation experiments. However, there is significant seasonal variability in the results for %Clay but this is more likely to be a result of sample contamination by the parent material than a reflection of seasonal influences (figure 4.24). PSD measures the distribution of different particle sizes and the %Clay content refers to clay-sized particles and is not a direct reference to clay minerals. Given that the greatest variability is in the 25-30cm samples, it is possible that the variability is caused by the inclusion of fine-grained chalky material in the sample. The results of the LOI analyses for $\%CaCO_3$ (calcium carbonate) confirm this variability with ranges from 26% to 61% in the samples collected at a depth of 25-30cm (appendix F).

The results for Fe (figure 4.20) and Mn (figure 4.21) are expected as the oxidation experiments are not going to increase or decrease the amount of total iron and manganese content of the soils but will affect the deposition of these minerals in their oxidised states. Again, there is some variation in the samples collected from 25-30cm but this is likely to be the result of varying quantities of $\%CaCO_3$ being included in the samples at collection. The results for EC in the soils after the oxidation experiment show some variation between experiment groups, in particular the 0-5cm sample from the oven dried experiment group (figure 4.27). This could be the result of organic material retaining moisture in the Ah horizon, thereby trapping more soluble salts than the other horizons.

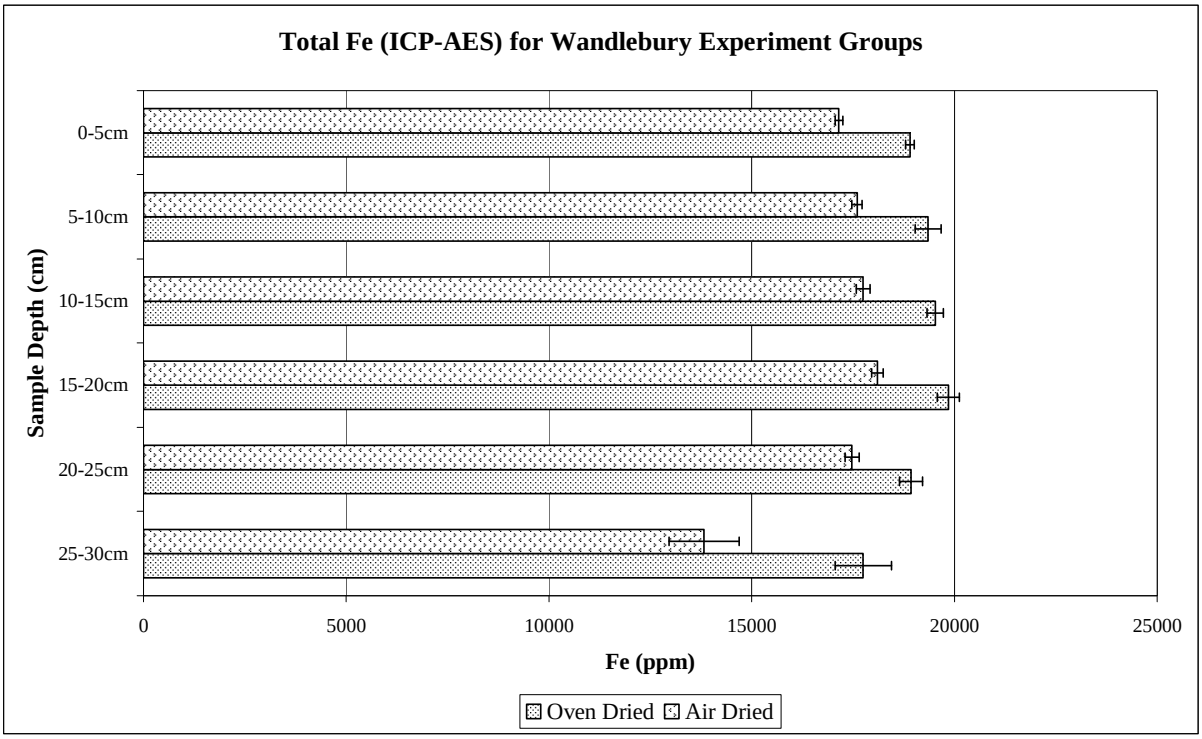


Figure 4.20. Mean and standard error for total Fe (ICP-AES) to determine seasonal variation for both the oven dried and air dried experiment groups.

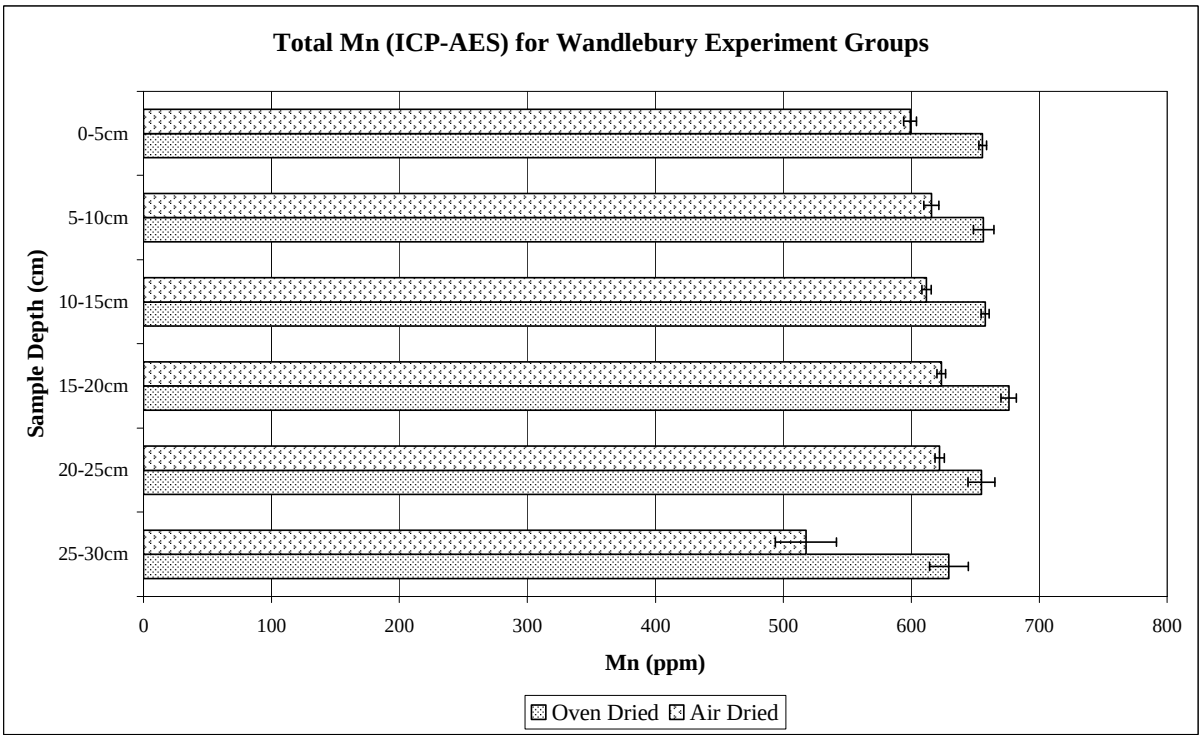


Figure 4.21. Mean and standard error for total Mn (ICP-AES) to determine seasonal variation for both the oven dried and air dried experiment groups.

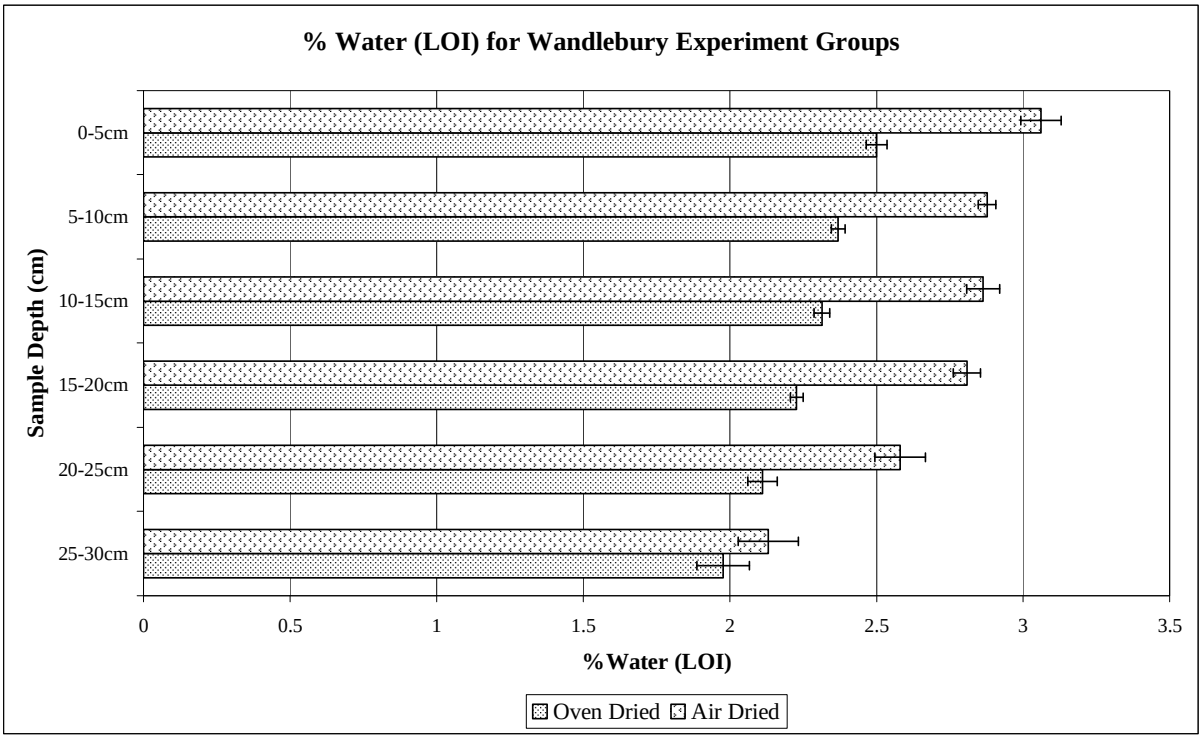


Figure 4.22. Mean and standard error for %Water (LOI) to determine seasonal variation for both the oven dried and air dried experiment groups.

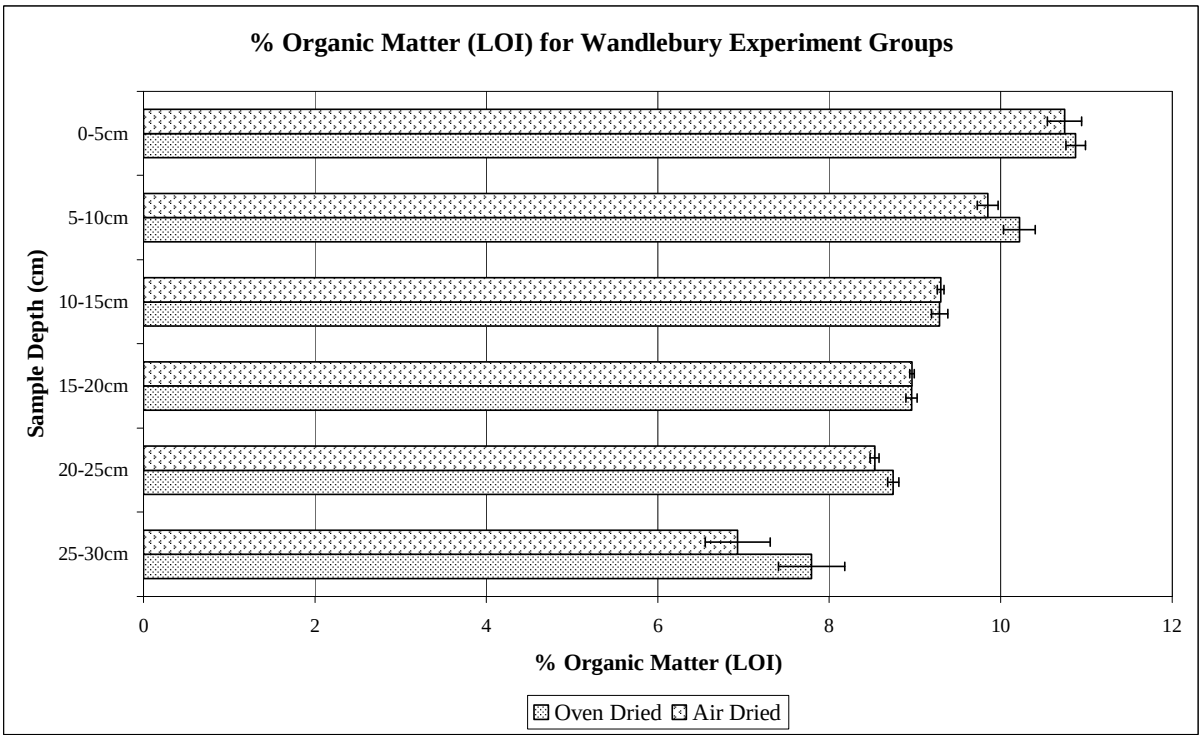


Figure 4.23. Mean and standard error for %Organic Matter (LOI) to determine seasonal variation for both the oven dried and air dried experiment groups.

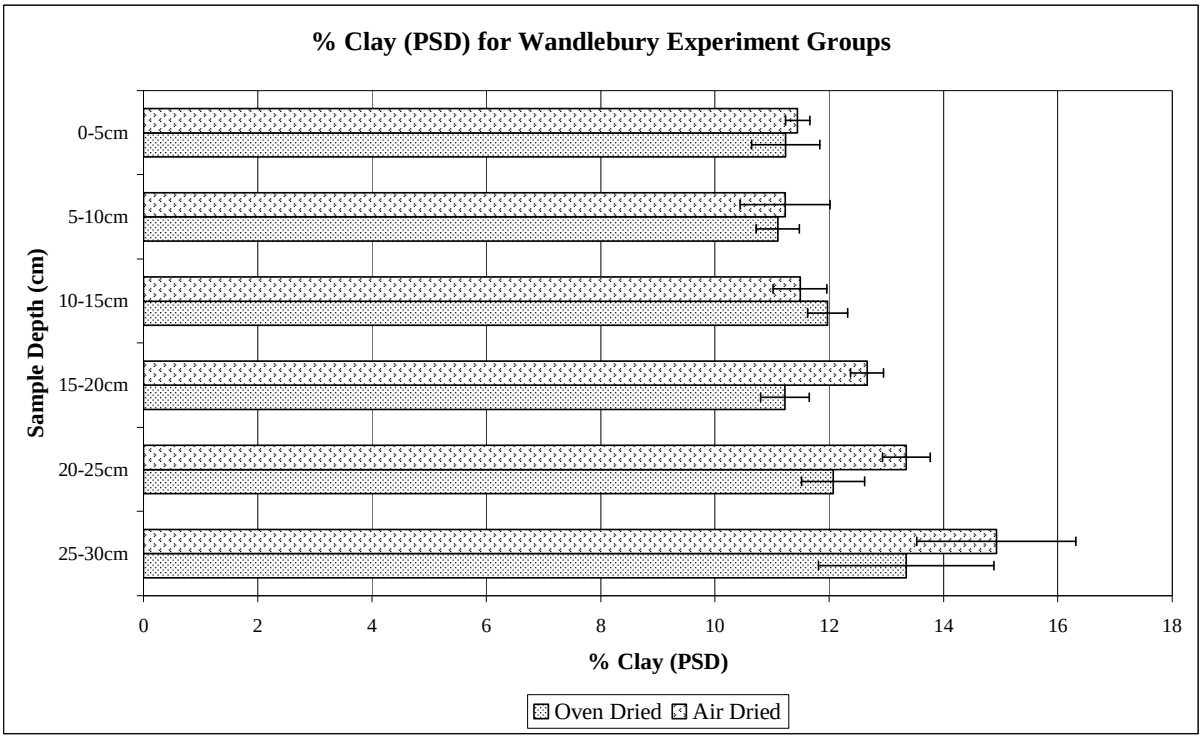


Figure 4.24. Mean and standard error for %Clay (PSD) to determine seasonal variation for both the oven dried and air dried experiment groups.

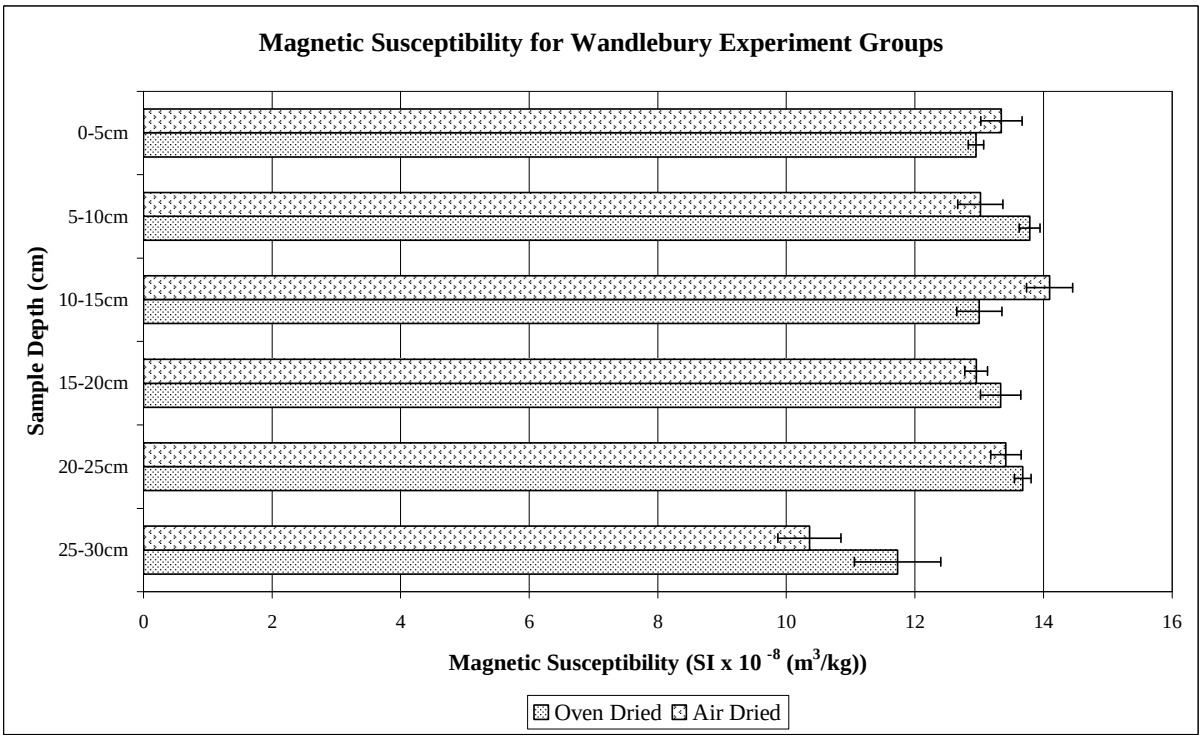


Figure 4.25. Mean and standard error for magnetic susceptibility to determine seasonal variation for both the oven dried and air dried experiment groups.

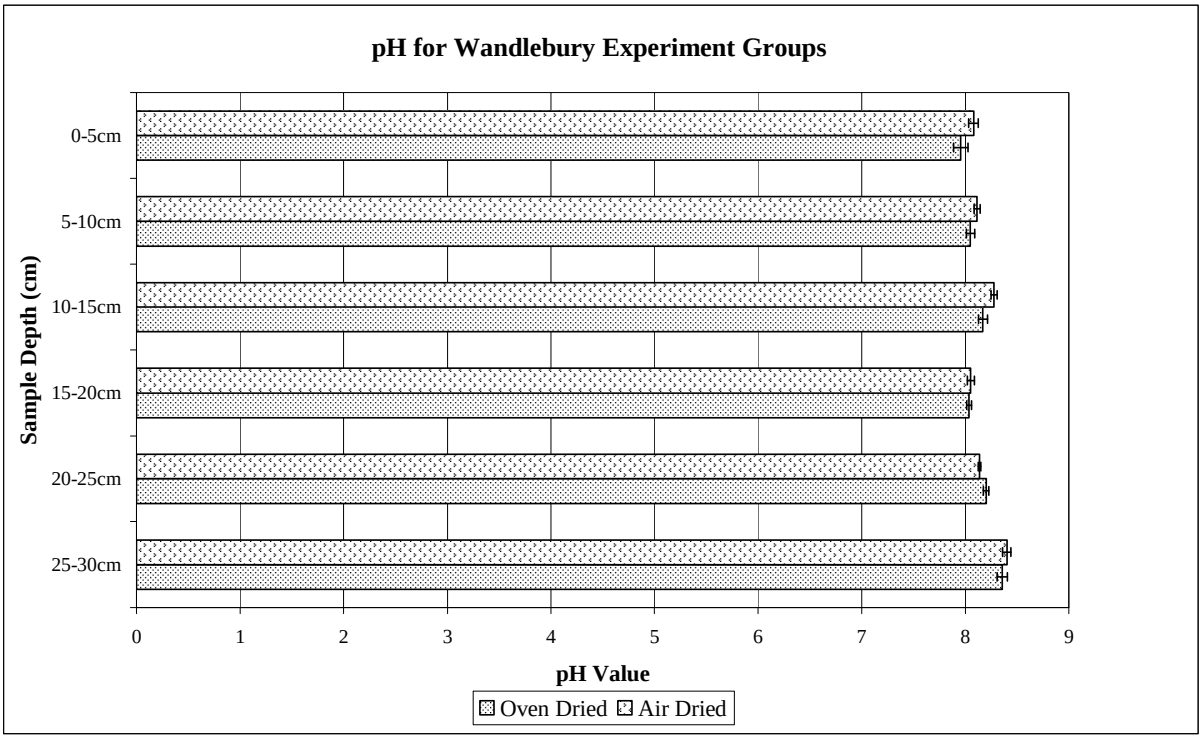


Figure 4.26. Mean and standard error for pH to determine seasonal variation for both the oven dried and air dried experiment groups.

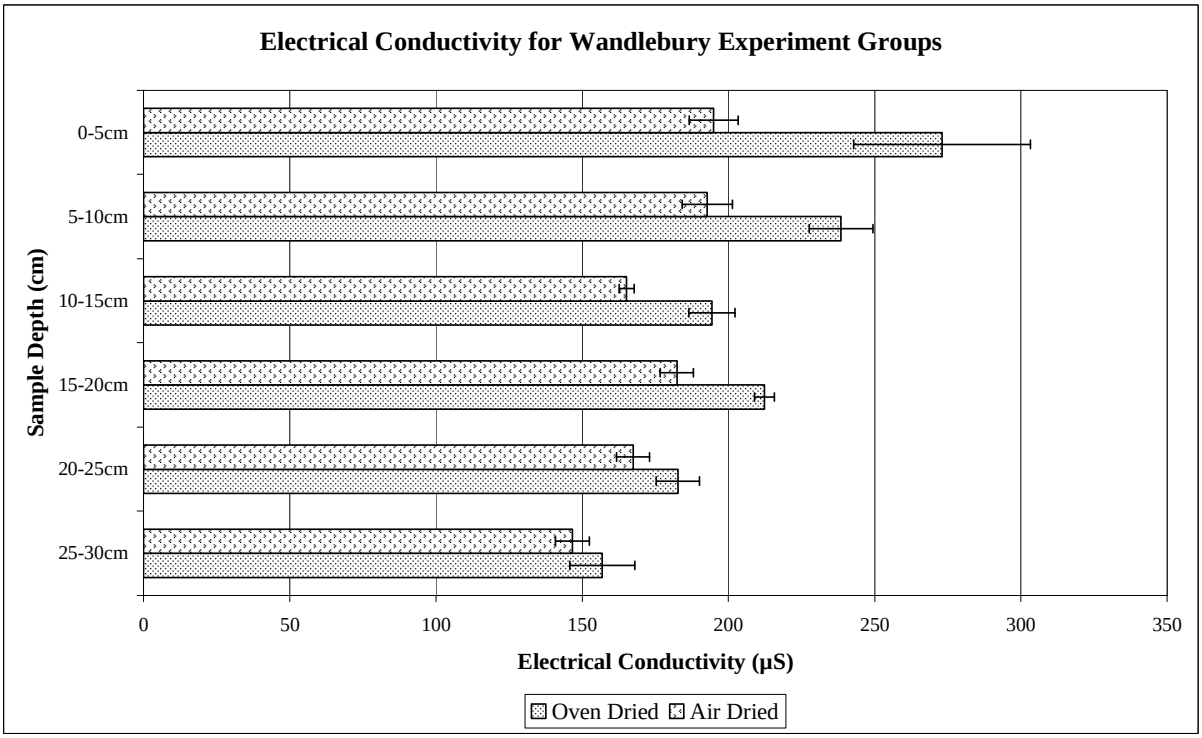


Figure 4.27. Mean and standard error for electrical conductivity to determine seasonal variation for both the oven dried and air dried experiment groups.

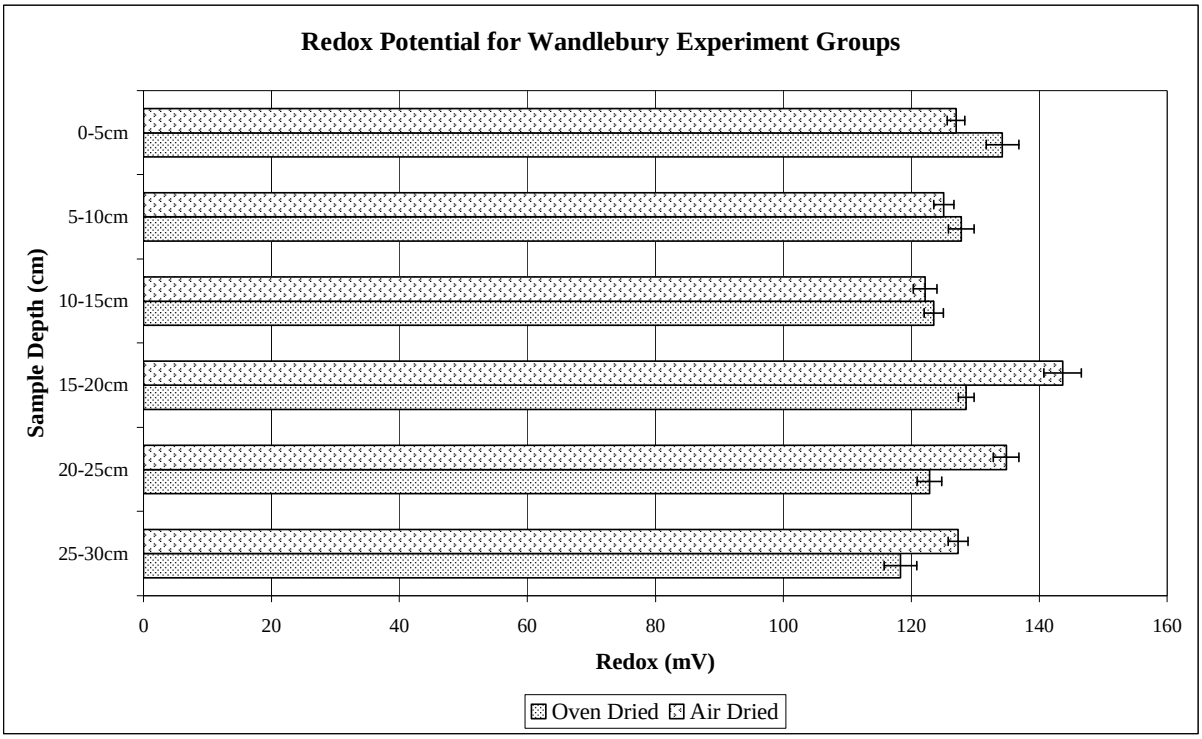


Figure 4.28. Mean and standard error for redox potential to determine seasonal variation for both the oven dried and air dried experiment groups.

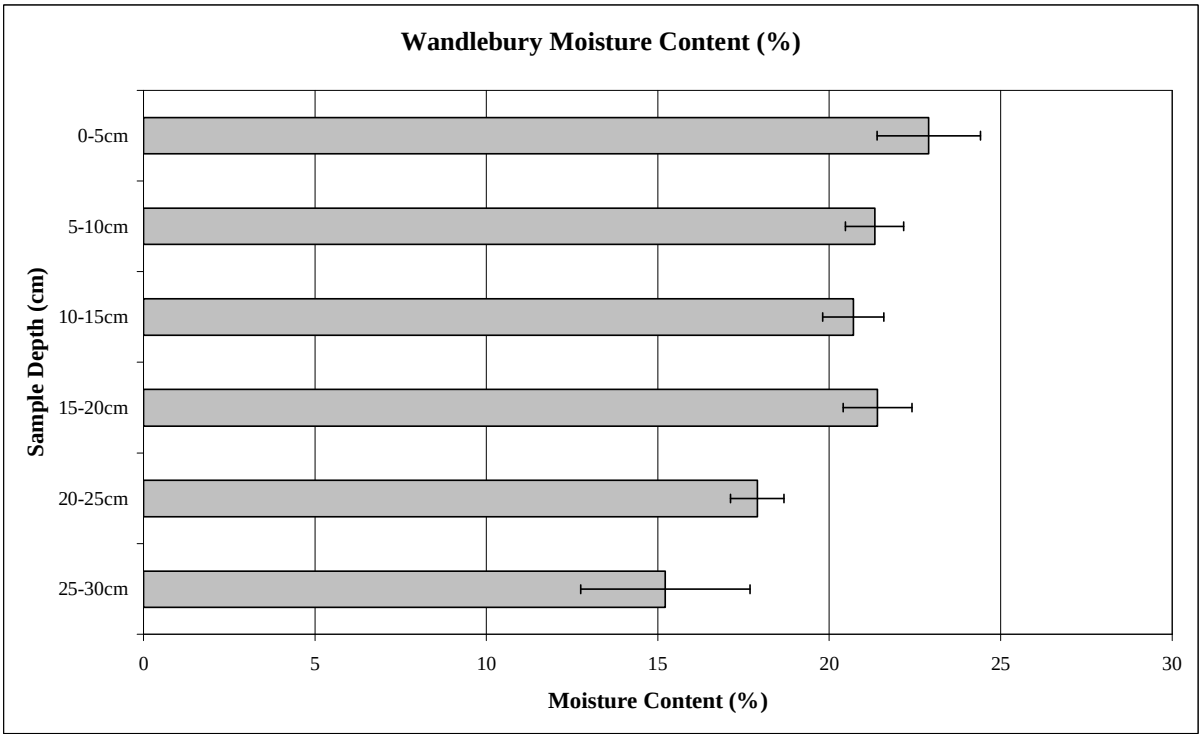


Figure 4.29. Mean and standard error to determine seasonal variation for the moisture content, taken prior to the oxidation experiments.

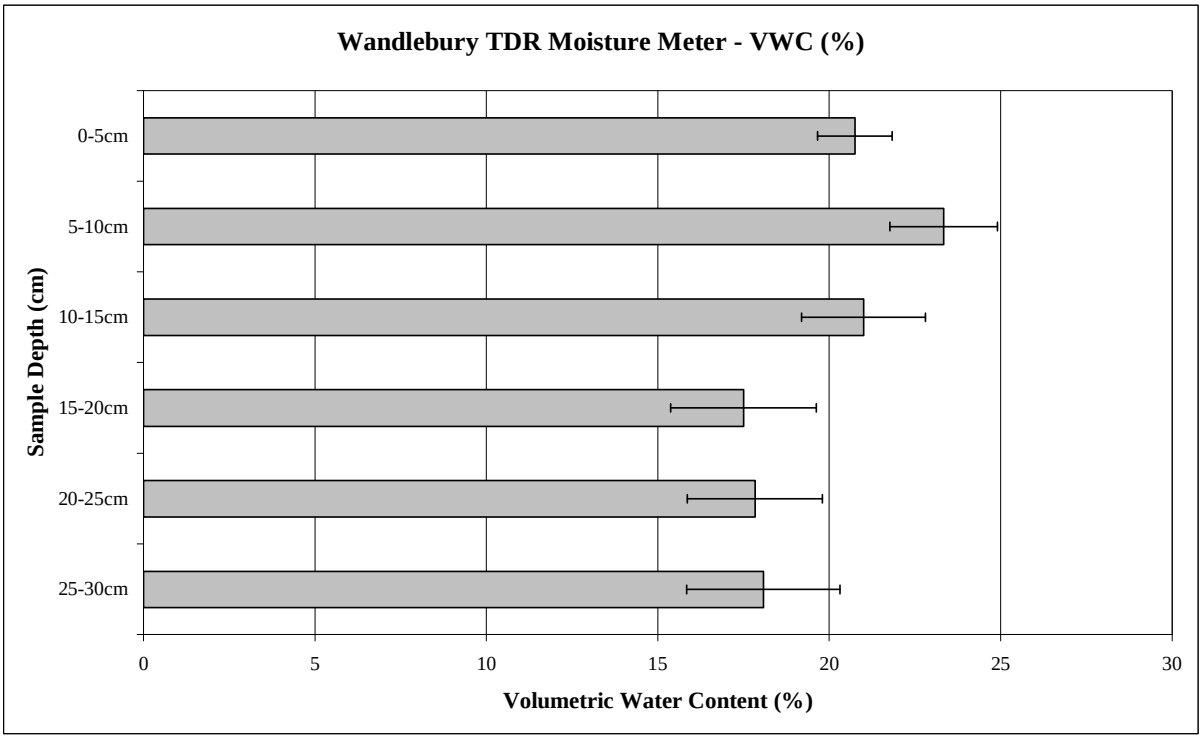


Figure 4.30. Mean and standard error to determine seasonal variation in soil moisture content for the in-field measurements taken prior to sampling.

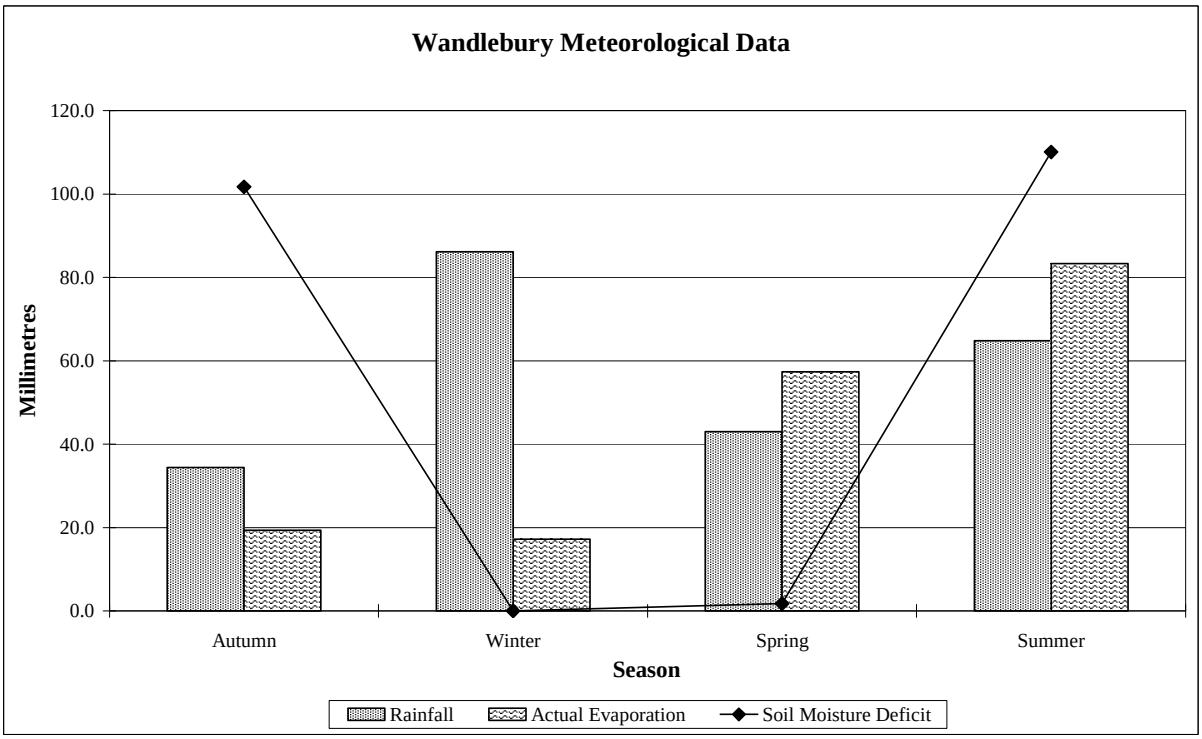


Figure 4.31. Rainfall, actual evaporation and soil moisture deficit for Wandlebury from autumn 2003 to summer 2004 (October 2003, January, April and July, 2004). This data was supplied by MORECS.

The results from the moisture content (figure 4.29), which is the percentage of moisture in the soil prior to the oxidation experiments, and the VWC from the in-field TDR moisture meter readings (figure 4.30) show more variation between seasons than the data from the other bulk analyses. This is expected as variation in rainfall and evaporation will have a direct influence on the moisture readings for the soil. The rainfall and evaporation records for the collection seasons show great variability with particularly dry seasons in autumn 2003 (which followed one of the driest summers on record in the UK) and summer 2004 (figure 4.31).

4.3.1.2 Correlation Coefficients and Relationships

As the data for the Wandlebury oven dried experiment group are normally distributed (table 4.6), Pearson's correlation coefficient was used to highlight relationships between the different analytical variables (Field 2005). However, the Wandlebury air dried experiment group were not normally distributed (table 4.7) so the Spearman's rho correlation was used (*ibid*). Although relationships between variables were expected, the direction of the relationships was not predicted; therefore, a two-tailed significance test was used (*ibid*). These results are presented in tables 4.8 and 4.9 below.

Table 4.8. Pearson correlation for all bulk analyses results for the Wandlebury oven dried experiment group. Significant correlations are highlighted.

Correlations for Wandlebury Oven Dried Experiment Group

		Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox (mV)	Bulk Density (%)	Volumetric Water Content (%)
Fe (ppm)	Pearson Correlation	1	.917**	.687**	-.772**	.639**	.460*	-.522**	.313	.270	.717**	.180
	Sig. (2-tailed)		.000	.000	.000	.001	.024	.009	.136	.202	.000	.399
	N	24	24	24	24	24	24	24	24	24	24	24
Mn (ppm)	Pearson Correlation	.917**	1	.570**	-.723**	.570**	.418*	-.460*	.289	.310	.663**	.125
	Sig. (2-tailed)	.000		.004	.000	.004	.042	.024	.171	.140	.000	.562
	N	24	24	24	24	24	24	24	24	24	24	24
Magnetic Susceptibility (SI Units)	Pearson Correlation	.687**	.570**	1	-.697**	.604**	.501*	-.551**	.281	.080	.584**	-.040
	Sig. (2-tailed)	.000	.004		.000	.002	.013	.005	.184	.709	.003	.854
	N	24	24	24	24	24	24	24	24	24	24	24
% Clay (PSD)	Pearson Correlation	-.772**	-.723**	-.697**	1	-.592**	-.507*	.379	-.248	-.352	-.652**	-.224
	Sig. (2-tailed)	.000	.000	.000		.002	.011	.067	.243	.091	.001	.292
	N	24	24	24	24	24	24	24	24	24	24	24
% Water (LOI)	Pearson Correlation	.639**	.570**	.604**	-.592**	1	.779**	-.821**	.718**	.367	.806**	.388
	Sig. (2-tailed)	.001	.004	.002	.002		.000	.000	.000	.078	.000	.061
	N	24	24	24	24	24	24	24	24	24	24	24
% Organic Matter (LOI)	Pearson Correlation	.460*	.418*	.501*	-.507*	.779**	1	-.560**	.512*	.589**	.506*	.060
	Sig. (2-tailed)	.024	.042	.013	.011	.000		.004	.010	.002	.012	.781
	N	24	24	24	24	24	24	24	24	24	24	24
pH Value	Pearson Correlation	-.522**	-.460*	-.551**	.379	-.821**	-.560**	1	-.904**	-.458*	-.789**	-.323
	Sig. (2-tailed)	.009	.024	.005	.067	.000	.004		.000	.024	.000	.124
	N	24	24	24	24	24	24	24	24	24	24	24
Electrical Conductivity (µS)	Pearson Correlation	.313	.289	.281	-.248	.718**	.512*	-.904**	1	.617**	.708**	.444*
	Sig. (2-tailed)	.136	.171	.184	.243	.000	.010	.000		.001	.000	.030
	N	24	24	24	24	24	24	24	24	24	24	24
Redox (mV)	Pearson Correlation	.270	.310	.080	-.352	.367	.589**	-.458*	.617**	1	.461*	.217
	Sig. (2-tailed)	.202	.140	.709	.091	.078	.002	.024	.001		.023	.308
	N	24	24	24	24	24	24	24	24	24	24	24
Bulk Density (%)	Pearson Correlation	.717**	.663**	.584**	-.652**	.806**	.506*	-.789**	.708**	.461*	1	.534**
	Sig. (2-tailed)	.000	.000	.003	.001	.000	.012	.000	.000	.023		.007
	N	24	24	24	24	24	24	24	24	24	24	24
Volumetric Water Content (%)	Pearson Correlation	.180	.125	-.040	-.224	.388	.060	-.323	.444*	.217	.534**	1
	Sig. (2-tailed)	.399	.562	.854	.292	.061	.781	.124	.030	.308	.007	
	N	24	24	24	24	24	24	24	24	24	24	24

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

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

Correlations with significance levels of $p<.05$ and $p<.01$ are marked by asterisks in each of the correlation tables. I will first discuss the correlations for the oven dried experiment group, followed by the air dried experiment group for Wandlebury.

In the oven dried experiment group (table 4.8) there are a number of significant relationships between Fe and other variables, including Fe and Mn (r = .917, $p<.0001$), Fe and MS (r = .687, $p<.0001$), Fe and %Clay (r = -.772, $p<.0001$), Fe and %Water (r = .639, $p<.001$), Fe and %OM (r = .460, $p<.05$), Fe and pH (r = -.522, $p<.01$), and Fe and moisture content (r = .717, $p<.0001$). The relationships between Fe and Mn and Fe and MS are expected for Wandlebury and suggest that the type of iron present in the soil has magnetic properties. Further, there is evidence of variable land use at the site including possible burning, which accounts for the extremely high MS readings (figure 4.39) (French *et al.* 2005b). Mn and MS are also correlated (r = .570, $p<.01$), which suggests that in addition to the land use history at the site, the elevated quantity of Mn (figure 4.21) in the soil at Wandlebury could account for the unusually high MS readings. The negative correlation between Fe and %Clay is actually representing the percentage of clay-sized $CaCO_3$, as discussed earlier, and therefore, this relationship is expected as the higher the calcium carbonate value, the lower the amount of Fe in the soil, as calcium carbonate is not always conducive to an iron-rich environment (cf. Stucki *et al.* 1988). The negative relationship between Fe and pH is expected as Fe is more common in acidic environments than alkaline environments, i.e. the higher the pH, the lower the quantity of Fe (*ibid*). The positive correlations between Fe and %Water and Fe and %OM suggest that the Fe that is present in the soil at Wandlebury is likely to be originating in the organic fraction of the soil and that the moisture present in the soil, after the oxidation experiments, is trapped within the organic material. This is confirmed by the strong positive correlation between %Water and %OM (r = .779, $p<.0001$). The micromorphological analyses below also reflect this relationship with the presence of iron replaced organic material and the generally organic-rich nature of the soils. Similar results are apparent for the relationship between moisture content and Fe, along with moisture content and %Water (r = .806, $p<.0001$), and moisture content and %OM (r = .506, $p<.05$), suggesting that the Fe and moisture content of the soil is held in the OM fraction of the soil.

Mn is correlated with the same variables as Fe, which is expected as these minerals behave similarly in the soil environment: Mn and %Clay (r = -.723, $p<.0001$), Mn and %Water (r = .570, $p<.01$), Mn and %OM (r = .418, $p<.05$), Mn and pH (r = -.460, $p<.05$), and Mn and moisture content (r = .663, $p<.0001$). In addition, MS is correlated with the same variables as

Fe and Mn (%Clay: r = -.697, p<.0001; %Water: r = .604, p<.01; %OM: r = .501, p<.05; pH: r = -.551, p<.01; moisture content: r = .584, p<.01), which confirms that the MS readings are most likely the result of the high amount of Mn and/or a magnetic form of Fe present in the soil environment. Further, the correlation between MS and %OM suggests that the plant nutrients present in the organic fraction of the soil contain magnetic properties and could be contributing to the high MS values (appendix G, table G-2).

As %Clay is in reference to clay-sized particles and not actually clay as a mineral component of the soil, %Clay represents the amount of clay-sized $CaCO_3$ particles, and the negative correlations between this variable and Fe (r = -.772, p<.0001), Mn (r = -.723, p<.0001) and MS (r = -.697, p<.0001) are expected as calcium carbonate is not conducive to high quantities of Fe and Mn, nor is it likely to have magnetic properties. The negative correlations between %Clay and %Water (r = -.592, p<.01), %Clay and %OM (r = -.507, p<.05), and %Clay and moisture content (r = -.652, p<.001) suggest that calcium carbonate is neither organic-rich, nor does it hold moisture very well. Further, the negative correlations between %Water and pH (r = -.821, p<.0001) and moisture content and pH (r = -.789, p<.0001) suggest that relative to the alkaline environment, the amount of moisture in the soil is low. Not surprisingly, there are positive correlations between %Water and EC (r = .718, p<.0001), moisture content and EC (r = .708, p<.0001), and VWC and EC (r = .444, p<.05), and the high readings for EC (figure 4.27) suggest that the moisture that is available in the soil is high in soluble salts.

The negative correlation between %OM and pH (r = -.560, p<.01) is expected in an alkaline environment, such as Wandlebury, as an increase in OM can cause an increase in acidity, and therefore, a decrease in pH. The relationship between EC and %OM (r = .512, p<.05) is also expected: as discussed above, the majority of the water containing the soluble salts is likely to have been trapped in the OM of the soil. The relationship between %OM and redox (r = .589, p<.01) could be a reflection of the breaking down of organic material in the soil by microbial activity, reflecting localised redox conditions, as discussed in chapter two.

The relationship between pH and EC (r = -.904, p<.0001) remains unclear, except that it reflects the relationship of pH with %Water and moisture content and given that EC is also correlated with these variables, this negative correlation may be reflecting these patterns for pH. The negative correlation between pH and redox (r = -.458, p<.05) makes sense in that more acidic environments are generally more conducive to redox processes than alkaline environments (Loeppert and Inskeep 1996).

Table 4.9. Spearman's rho correlation was used for the Wandlebury air dried experiment group as the data are not normally distributed. Significant correlations are highlighted.

Correlations for Wandlebury Air Dried Experiment Group

			Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox (mV)	Bulk Density (%)	Volumetric Water Content (%)
Spearman's rho	Fe (ppm)	Correlation Coefficient	1.000	.739**	.140	.001	.202	.170	-.199	.043	.030	-.021	.090
		Sig. (2-tailed)	.	.000	.513	.995	.344	.428	.352	.843	.888	.923	.675
		N	24	24	24	24	24	24	24	24	24	24	24
	Mn (ppm)	Correlation Coefficient	.739**	1.000	.172	.198	.148	.084	-.163	-.003	.069	-.178	-.089
		Sig. (2-tailed)	.000	.	.422	.353	.490	.696	.447	.989	.748	.407	.678
		N	24	24	24	24	24	24	24	24	24	24	24
	Magnetic Susceptibility (SI Units)	Correlation Coefficient	.140	.172	1.000	-.427*	.318	.338	-.210	-.231	-.115	.117	-.098
		Sig. (2-tailed)	.513	.422	.	.037	.130	.106	.325	.277	.593	.585	.649
		N	24	24	24	24	24	24	24	24	24	24	24
	% Clay (PSD)	Correlation Coefficient	.001	.198	-.427*	1.000	-.375	-.303	.100	-.017	.271	-.304	-.274
		Sig. (2-tailed)	.995	.353	.037	.	.071	.149	.643	.939	.201	.148	.194
		N	24	24	24	24	24	24	24	24	24	24	24
	% Water (LOI)	Correlation Coefficient	.202	.148	.318	-.375	1.000	.745**	-.305	.292	.128	.417*	.557**
		Sig. (2-tailed)	.344	.490	.130	.071	.	.000	.147	.166	.551	.042	.005
		N	24	24	24	24	24	24	24	24	24	24	24
	% Organic Matter (LOI)	Correlation Coefficient	.170	.084	.338	-.303	.745**	1.000	-.347	.464*	-.241	.328	.357
		Sig. (2-tailed)	.428	.696	.106	.149	.000	.	.096	.022	.256	.118	.087
		N	24	24	24	24	24	24	24	24	24	24	24
	pH Value	Correlation Coefficient	-.199	-.163	-.210	.100	-.305	-.347	1.000	-.693**	-.228	-.513*	-.121
		Sig. (2-tailed)	.352	.447	.325	.643	.147	.096	.	.000	.285	.010	.574
		N	24	24	24	24	24	24	24	24	24	24	24
	Electrical Conductivity (µS)	Correlation Coefficient	.043	-.003	-.231	-.017	.292	.464*	-.693**	1.000	.093	.477*	.382
		Sig. (2-tailed)	.843	.989	.277	.939	.166	.022	.000	.	.665	.019	.065
		N	24	24	24	24	24	24	24	24	24	24	24
	Redox (mV)	Correlation Coefficient	.030	.069	-.115	.271	.128	-.241	-.228	.093	1.000	.314	.054
		Sig. (2-tailed)	.888	.748	.593	.201	.551	.256	.285	.665	.	.135	.803
		N	24	24	24	24	24	24	24	24	24	24	24
	Bulk Density (%)	Correlation Coefficient	-.021	-.178	.117	-.304	.417*	.328	-.513*	.477*	.314	1.000	.487*
		Sig. (2-tailed)	.923	.407	.585	.148	.042	.118	.010	.019	.135	.	.016
		N	24	24	24	24	24	24	24	24	24	24	24
	Volumetric Water Content (%)	Correlation Coefficient	.090	-.089	-.098	-.274	.557**	.357	-.121	.382	.054	.487*	1.000
		Sig. (2-tailed)	.675	.678	.649	.194	.005	.087	.574	.065	.803	.016	.
		N	24	24	24	24	24	24	24	24	24	24	24

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

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

Finally, the positive correlations between redox and EC (r = .617, p<.001) and redox and moisture content (r = .461, p<.05) suggest a relationship between redox processes and soil water content, which is expected, and along with the correlations of redox with OM and OM with moisture content, suggest that the majority of the moisture in the soil is in the OM. However, as the groundwater table is well below the modern soil and upper chalk substrate, the redox processes are more likely to be the result of biological activity, which is evident in the presence of mite and earthworm excrements identified by the soil micromorphological analyses (appendix F).

In the air dried experiment group (table 4.9) there is a positive correlation between Fe and Mn (r_s = .739, p<.0001), which is expected as these minerals are usually associated and behave in similar ways in the soil environment. Similar to the oven dried experiment group, there is a negative correlation between %Clay and MS (r_s = -.427, p<.05) in the air dried experiment group, which suggests that the %Clay is representing %$CaCO_3$ and is not magnetically susceptible. The correlation between %OM and %water (r_s = .745, p<.0001) in the air dried experiment group suggests that the available moisture in the soil is being held in the OM. Further, the correlations between %Water and moisture content (r_s = .417, p<.05) and %Water and VWC (r_s = .557, p<.01) suggest that this moisture is retained before and after the oxidation experiment, albeit in smaller quantities post oxidation (figures 4.22, 4.29 and 4.30).

The negative correlations between pH and EC (r_s = -.693, p<.0001) and between pH and moisture content (r_s = -.513, p<.05), and the positive correlation between moisture content and EC (r_s = .477, p<.05) reflect the results for the oven dried experiment group, where pH, EC and moisture are all intimately connected. In addition, the positive correlation between EC and %OM (r_s = .464, p<.05) reflects the results for the oven dried experiment group, suggesting that the available moisture in the soil, and its soluble salts, are held within the organic component of the soil.

Finally, the correlation between moisture content and VWC (r_s = .534, p<.01) is present in tables 4.8 and 4.9. The correlations in these tables are identical as they were taken as a control for the moisture in the soil prior to the drying out experiments. The strong positive correlation between these variables confirms the accuracy of both methods: moisture content is a measure of soil moisture before drying out, and is as close to in-field moisture levels as possible in a laboratory environment, and VWC is a direct in-field reading of the soil moisture content at Wandlebury.

4.3.2 Soil Micromorphology

Soil micromorphological analyses were carried out for each experiment group: oven dried, air dried and control, with particular focus on microstructure, relative porosity, iron oxide deposition, and organic material (appendix F). The descriptions follow Bullock *et al.* (1985) and Stoops (2003) and the coarse-fine limit for the soils at Wandlebury is set at 20µm. I will first provide a brief description of the soil microstructure and porosity, followed by more detail on iron oxide deposition and organic material.

4.3.2.1 Microstructure and Porosity

The fine fraction of the soil at Wandlebury is an iron and calcite rich silty clay with a subrounded blocky to crumby structure. The coarse-fine distribution is single spaced porphyric with a ratio of 2:3, suggesting that the soil is dominated by its fine fabric component. While predominantly crystallitic, there is some stipple speckling indicating the presence of unoriented clay. Given the chalky substrate of this soil, there are some chalk inclusions in the B horizon. The areas where crumb structure is dominant indicate bioturbation, most likely from earthworms, as crystallitic earthworm granules were common throughout the soil profile. The presence of channel voids also suggests some root activity along with natural soil development.

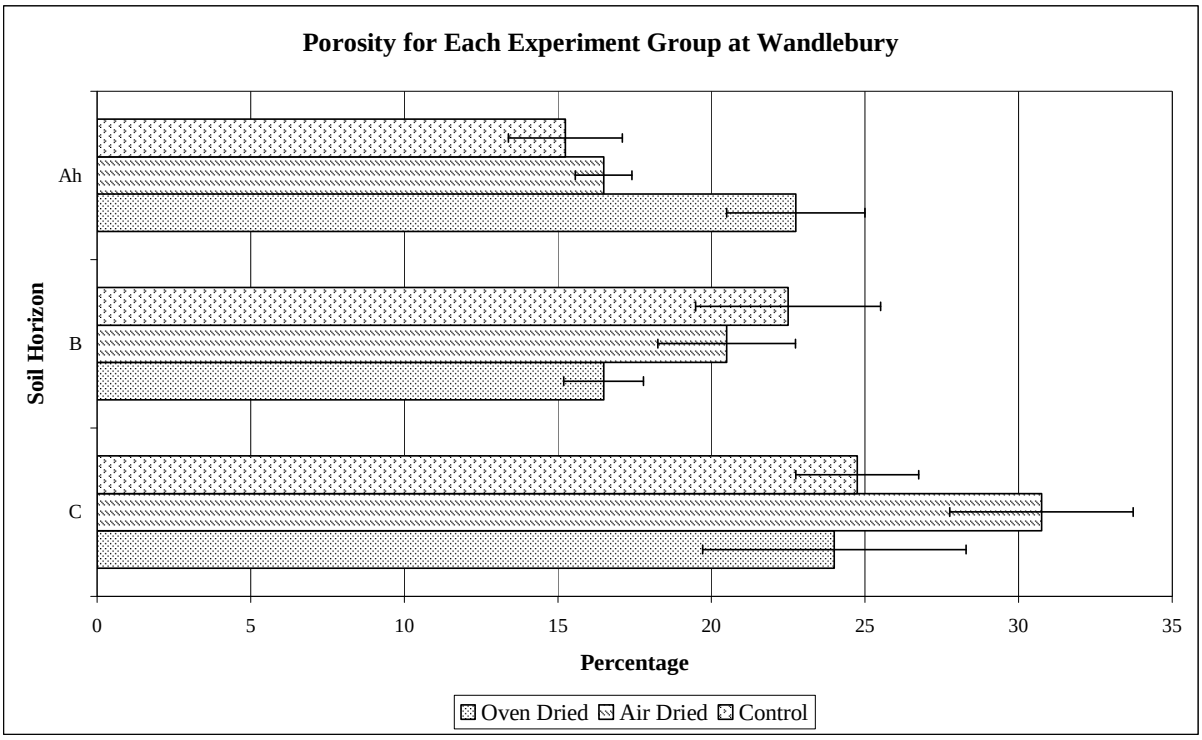


Figure 4.32. Mean porosity (%) and seasonal variation (error bars) for the soils at Wandlebury for all experiment groups.

The porosity of the soil is dominated by both channels and vughs and the mean percentage of porosity does illustrate some variation both seasonally and between experiment groups (figure 4.32). Although it is tempting to suggest that this variability is the direct result of the oxidation experiments, the results observed for the control group suggest that this is unlikely. Instead, the variation in porosity is more likely the result of earthworm activity in the soil profile, which aerates the soil and ultimately increases the amount of oxygen in the soil environment, and therefore, the porosity of the soil.

4.3.2.2 Iron Oxide Deposition

The iron oxide deposition present at Wandlebury includes staining, nodules, coatings and replacement of organic material (pseudomorphs). There are no pans present at this site. There is some variation in the presence of iron coatings of grains and voids between experiment groups at Wandlebury, more so in the upper horizons (figure 4.33). The distribution of the coatings down profile suggests that illuviation is not a prevalent process at Wandlebury, although the voluminous presence of calcite in the fabric masks much of the lower horizons. There is also some seasonal variation, which may be attributed to the seasonal variation in rainfall. Coatings result from illuviation processes whereby iron-rich clay moves through the

soil profile by the capillary action of the soil and through movement down profile in colloidal suspension with rainwater (Limbrey 1975).

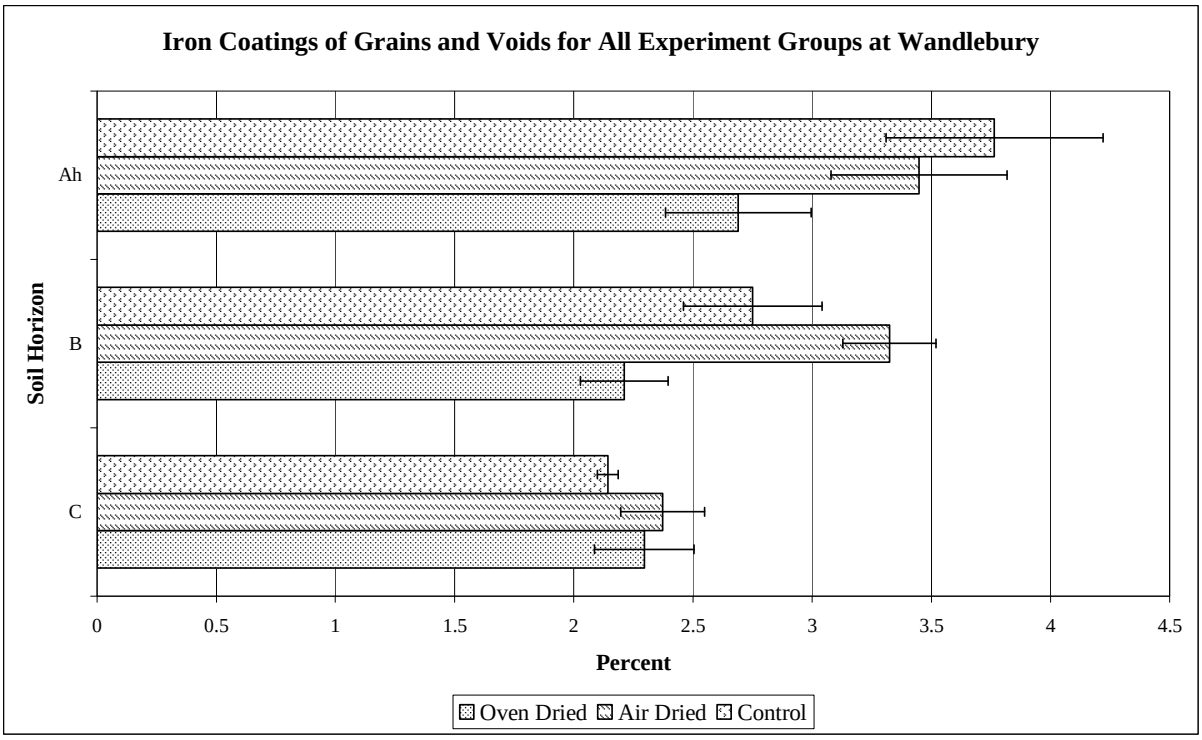


Figure 4.33. Mean percentage of coatings and seasonal variation (error bars) for all experiment groups at Wandlebury.

There appears to be a significant amount of organic replacement present in the soils at Wandlebury (table 4.10). In the absence of a fluctuating groundwater table, some other variable must be the cause of redox processes in order for the pseudomorphs to occur. In this instance it is likely that reducing-oxidising cycles are the result of micro-organisms present in the soil. As organic material is a good source of iron, it makes sense that in the decomposition of the organic material iron is released making it available for consumption and respiration for available micro-organisms (Limbrey 1975; Stucki *et al.* 1988).

Table 4.10. Results for the percentage of iron replacement of organic matter, as identified through soil micromorphological analysis.

Sample Number		Soil Horizon	Replacement		
			Frequency	Minimum (µm)	Maximum (µm)
October 2003	**1.1**	Ah	■	233	333
	1.2	B	■	400	400
	1.3	C	■	50	350
	2.1	Ah	■■	110	316
	2.2	B	■	100	130
	2.3	C	■	83	117
	3.1	Ah	■■	100	243
	3.2	B	■■■	88	450
	3.3	C	■	50	275
January 2004	**1.1**	Ah	■	115	300
	1.2	B	■	80	280
	1.3	C	■	175	268
	2.1	Ah	■■	128	325
	2.2	B	■■■	57	277
	2.3	C	■	94	324
	3.1	Ah	■■■	75	220
	3.2	B	■	80	100
	3.3	C			
April 2004	**1.1**	Ah	■	100	217
	1.2	B	■	100	400
	1.3	C	■	260	260
	2.1	Ah	■■■	120	330
	2.2	B	■■	150	300
	2.3	C			
	3.1	Ah	■■	90	350
	3.2	B	■	83	300
	3.3	C	■	100	400
July 2004	**1.1**	Ah	■	80	250
	1.2	B	■	57	163
	1.3	C	■	517	583
	2.1	Ah	■■	108	425
	2.2	B	■■	220	390
	2.3	C	■	150	150
	3.1	Ah	■	125	400
	3.2	B	■	80	260
	3.3	C	■	50	360

Key: ■ <2%, ■■ 2-5%, ■■■ 5-10%, ■■■■ 10-20%, ■■■■■ 20-30%, ■■■■■■ 30-40%, ■■■■■■■ 40-50%, ■■■■■■■■ 50-60%, ■■■■■■■■■ 60-70%

Iron coatings and replacement of organic material are not likely to be affected by the oxidation experiments but do tell us something about the soil environment present at Wandlebury. Iron nodules and staining, on the other hand, are more susceptible to changes in the level of oxygen introduced into the soil environment. Figures 4.34 to 4.36 show how these changes in oxidation rates affect the presence of iron nodules and iron staining.

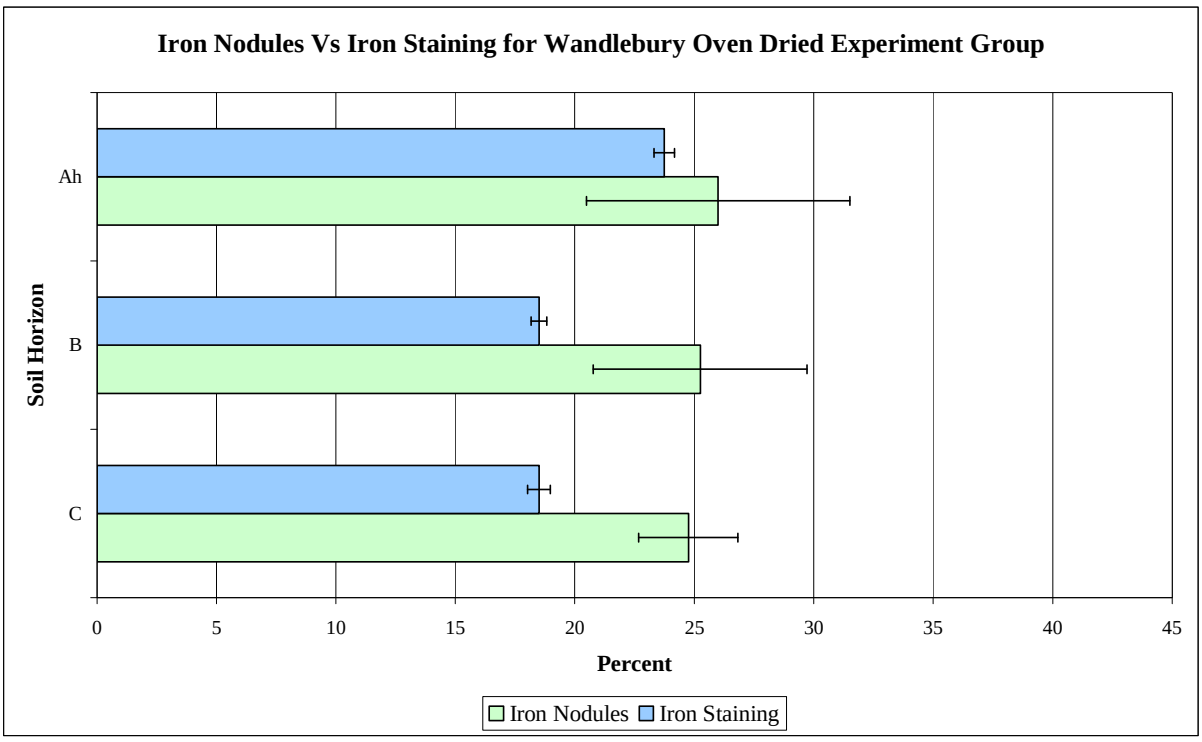


Figure 4.34. Mean percentage of iron nodules and iron staining, and the seasonal variation (error bars) for the oven dried experiment group at Wandlebury.

Figure 4.34 shows that iron nodules are more prevalent than iron staining in the oven dried experiment group, which confirms that iron nodules form in reaction to rapid oxidation. Conversely, figure 4.35 shows that iron staining is more prevalent than iron nodules in the air dried experiment group, which confirms that iron staining forms in reaction to slow oxidation. The results for the control group (figure 4.36) show that iron staining is more prevalent than iron nodules. As the control group were sampled as an *in situ* representation of the soil environment at Wandlebury, this result could reflect the land use history of the area, which includes not only pastoral use but also agricultural activities, and it is likely that some burning has taken place on this landscape. Finally, there appears to be some seasonal variation in the percentage of iron nodules for each experiment group. This may be the result of variation in the amount of soil moisture within the soil, and therefore, variable amounts of ferrous iron to oxidise into nodular ferric iron.

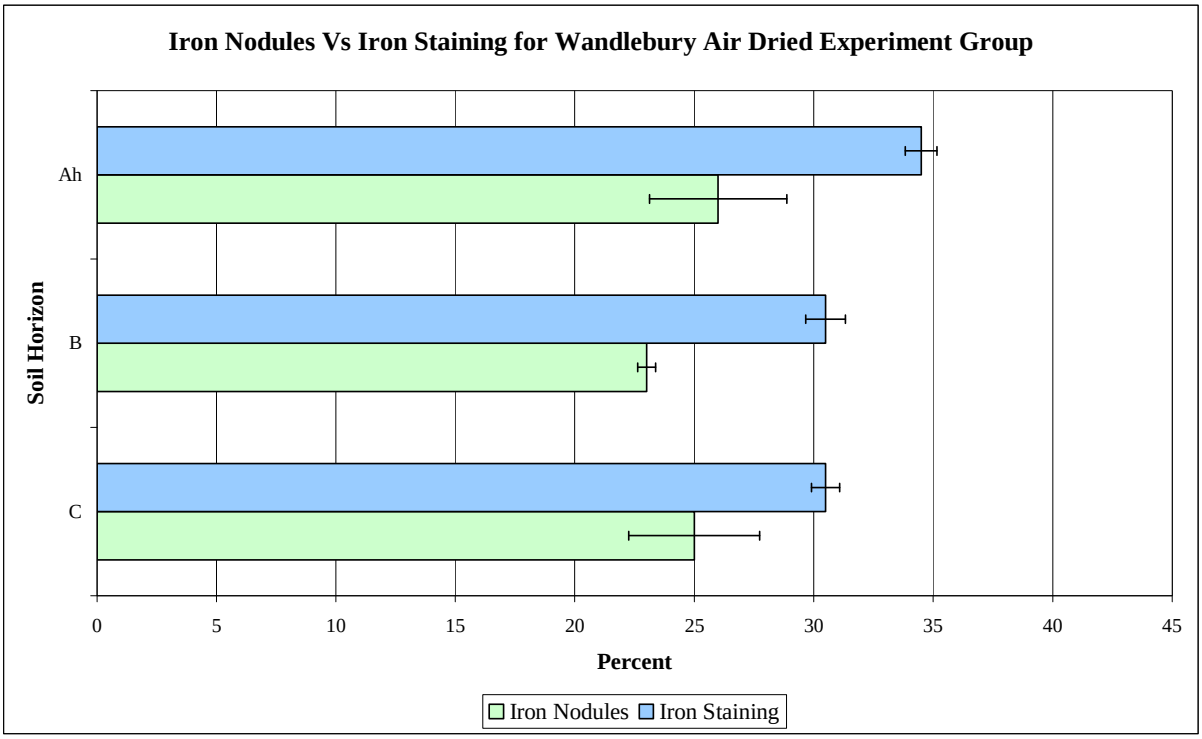


Figure 4.35. Mean percentage of iron nodules and iron staining, and the seasonal variation (error bars) for the air dried experiment group at Wandlebury.

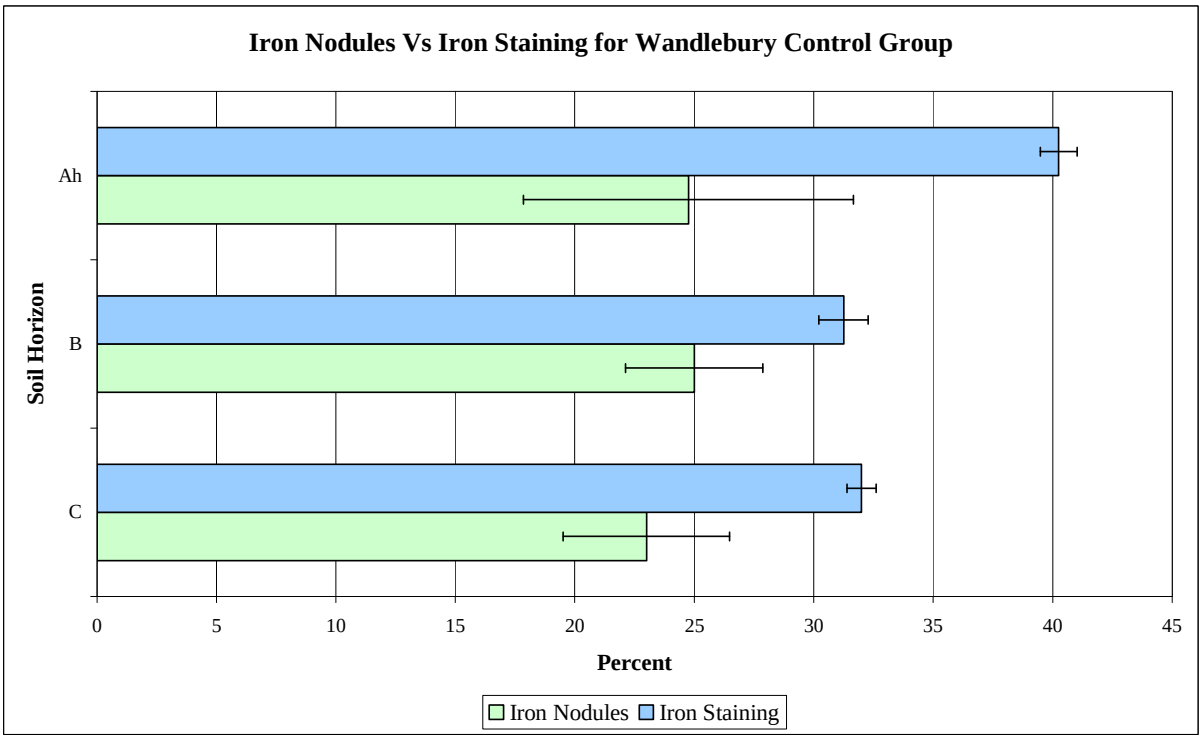


Figure 4.36. Mean percentage of iron nodules and iron staining, and the seasonal variation (error bars) for the control group at Wandlebury.

4.3.2.3 Organic Material

Table 4.11 presents the percentage frequencies and preservation state for the organic material identified through soil micromorphological analysis. In addition to the frequencies and the state of preservation of the organic material, the size range for celled material, and whether or not the organic material is associated with iron oxide, is also noted (appendix F).

The soils at Wandlebury are rich in organic material and are dominated by fine organic punctuations and amorphous organic matter. This is most likely the result of both the general oxidising conditions of the soil and the faunal activity within the soil, evident through crystallitic earthworm excretions. There does not appear to be great variation either seasonally or between oxidation experiments. Charcoal is also evident throughout the profile in ranges both above and below 100µm, which can be attributed to past land use at the site. Celled organic material is also present in various stages of decomposition, although the pattern of distribution suggests that no clear link can be made between the organic material and oxidation experiments. As discussed earlier, the decomposition of the celled plant material is ranked by number, 1 being the least decayed and 5 being the most decayed. The predominance of organic material in the red-brown stage would indicate that iron is being released from the organic material at this stage of decomposition (Babel 1981). This process may be attributed to microbial activity, along with the aeration of the soil via bioturbation. While the level of preservation of the organic material at Wandlebury cannot be directly linked to the effects of the oxidation experiments, it does provide valuable information about the processes occurring within the natural soil environment.

Table 4.11. Percentage of organic material for Wandlebury identified through micromorphological analysis.

Sample Number		Soil Horizon	Amorphous		Charcoal		Celled			Plectenchyma (Fungi)	Pollen
			Punctuations	Matter	< 100um	> 100um	Lignified	Parenchymatic	Phlobaphene		
October 2003	1.1	Ah	■■■■■■■	■■■■■	■■■	■		■ 1-3	■ 1-3	■ 4-5	
	1.2	B	■■■■■■■	■■■■■	■■■■	■■	■ 1-3	■ 1	■ 1-3		
	1.3	C	■■■■■■■	■■■■■	■■■	■■	■ 1-3	■ 5	■ 1-3		■
	2.1	Ah	■■■■■■■	■■■■	■■■■	■■	■ 1-2	■ 1-2	■ 1-2		
	2.2	B	■■■■■■■	■■■■	■■■	■■		■ 1-5		■ 3-5	
	2.3	C	■■■■■■■	■■■■	■■■■	■		■ 1-2		■ 3-5	■
	3.1	Ah	■■■■■■■	■■■■■	■■■■	■■	■ 1-2	■ 1-3	■ 3	■ 3-5	
	3.2	B	■■■■■■■	■■■■	■■■	■■	■ 1-2	■ 2-3	■ 3		
	3.3	C	■■■■■■■	■■■■	■■■	■■	■ 1-4	■ 1-2			■
January 2004	1.1	Ah	■■■■■■■	■■■■	■■■	■	■■ 1-3		■ 1-3	■ 4-5	■
	1.2	B	■■■■■■■	■■■■	■■■	■	■ 1	■ 1-3			■
	1.3	C	■■■■■■■	■■■■	■■■	■					
	2.1	Ah	■■■■■■■	■■■■	■■■	■■		■ 1-3			■
	2.2	B	■■■■■■■	■■■■	■■■■	■■■	■ 2-3				■
	2.3	C	■■■■■■■	■■■■	■■■	■■	■ 1-2				■
	3.1	Ah	■■■■■■■	■■■■■	■■■	■	■■ 1-2	■ 1-2		■ 3-5	■
	3.2	B	■■■■■■■	■■■■	■■■	■■	■■ 2-5		■ 3	■ 3-5	■
	3.3	C	■■■■■■■	■■■■	■■■	■■	■ 1-2		■■■ 3	■ 3-5	■
April 2004	1.1	Ah	■■■■■■■	■■■■	■■■	■■	■■ 1-3	■ 1-3	■ 3	■ 3-5	
	1.2	B	■■■■■■■	■■■■	■■■	■■	■ 1-3			■ 3-5	■
	1.3	C	■■■■■■	■■■■	■■■	■	■ 2-3				■
	2.1	Ah	■■■■■■■	■■■■■	■■■	■	■ 4-5	■ 1-4			■
	2.2	B	■■■■■■■	■■■■	■■■	■	■ 2-5	■ 3-5	■ 3		■
	2.3	C	■■■■■■■	■■■■	■■■	■					
	3.1	Ah	■■■■■■■	■■■■■	■■■	■■	■■■ 1-3	■■ 1-2	■ 3		
	3.2	B	■■■■■■■	■■■■	■■■	■	■■ 1-3	■ 2-3	■■ 3	■ 3-5	■
	3.3	C	■■■■■■■	■■■■	■■■■	■■	■■ 2-3	■ 1-2	■ 3	■ 3-5	■
July 2004	1.1	Ah	■■■■■■■	■■■■■	■■■	■	■ 2-3	■ 3			■
	1.2	B	■■■■■■■	■■■■	■■■	■■				■ 3	■
	1.3	C	■■■■■■■	■■■■	■■■	■■				■ 3-5	■
	2.1	Ah	■■■■■■■	■■■■■	■■■	■■	■ 1-3	■ 1-3			■
	2.2	B	■■■■■■■	■■■■	■■■	■■		■ 1			■
	2.3	C	■■■■■■■	■■■■	■■■	■	■ 1-3			■ 4-5	■
	3.1	Ah	■■■■■■■	■■■■■	■■■	■■	■■ 1-3	■ 2-3	■ 3	■ 3-5	■
	3.2	B	■■■■■■■	■■■■	■■■	■	■■ 2-3	■ 3-5	■ 3		■
	3.3	C	■■■■■■■	■■■■	■■■	■	■ 2-3	■ 3-5	■ 3	■ 3-5	■

Key: ■ <2%, ■■ 2-5%, ■■■ 5-10%, ■■■■ 10-20%, ■■■■■ 20-30%, ■■■■■■ 30-40%, ■■■■■■■ 40-50%, ■■■■■■■■ 50-60%, ■■■■■■■■■ 60-70%

Key to preservation of organic material: 1 = fresh; 2 = yellow; 3 = red-brown; 4 = brown; 5 = black

4.3.3 CDB for a Rendzina

The bulk and micromorphological data for Wandlebury reveal little seasonal variation or variation between experiment groups. The most noteworthy feature of the soils at Wandlebury is the high magnetic susceptibility in conjunction with high quantities of iron and manganese. As highlighted earlier, this is likely to be a direct result of past land use at Wandlebury. In addition, the iron and manganese present at Wandlebury most likely originates from the organic component of the soil, as is supported by the bulk analyses data correlations, and evidence of biotic redox processes and organic decomposition present in the more organic-rich horizons of the soil profile.

The comparative database (CDB), as represented by the two graphs below (figures 4.37 and 4.38), was formed by combining the bulk and soil micromorphological data for the experiment groups at Wandlebury. These graphs highlight the variables that are most likely to provide the best representation of the oxidation environment within the soil, in a way that is functional and clear as a reference guide to gauging preservation.

Given the lack of significant seasonal variation for each of the bulk and micromorphological analyses, the means for each variable have been used to formulate the graphs in figures 4.37 and 4.38 in reference to their soil depth and soil horizon. For each figure, a sedimentological key is provided to represent the soil profile at the site, and the corresponding bulk and soil micromorphological results are mapped out in accordance with their context in the soil profile. Two variables from the soil micromorphological analyses have been used for these graphs: iron nodules and iron staining, as these variables prove the most informative for determining the oxidation and/or hydrological environment for a typical rendzina such as Wandlebury.

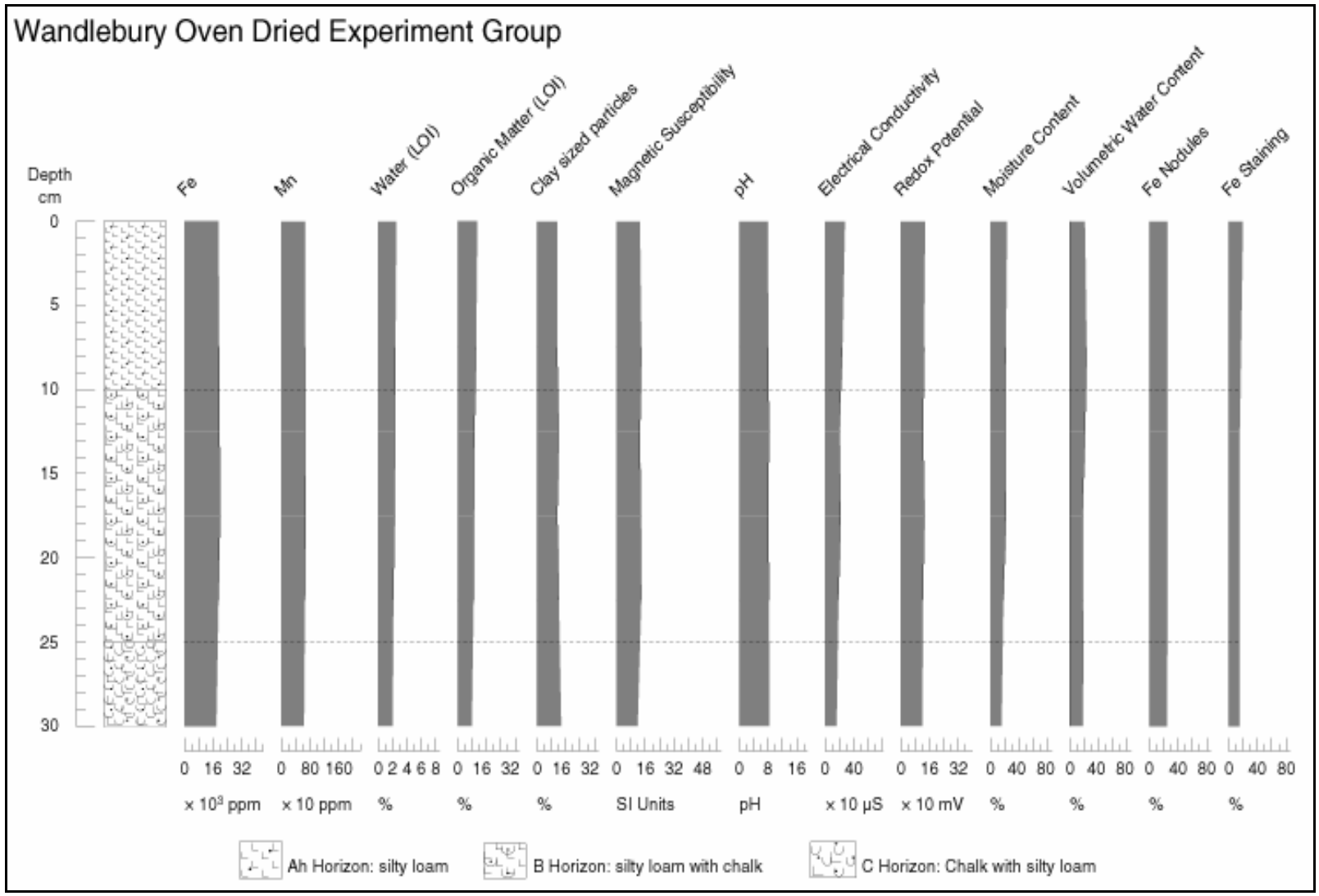


Figure 4.37. The comparative database (CDB) for the Wandlebury oven dried experiment group.

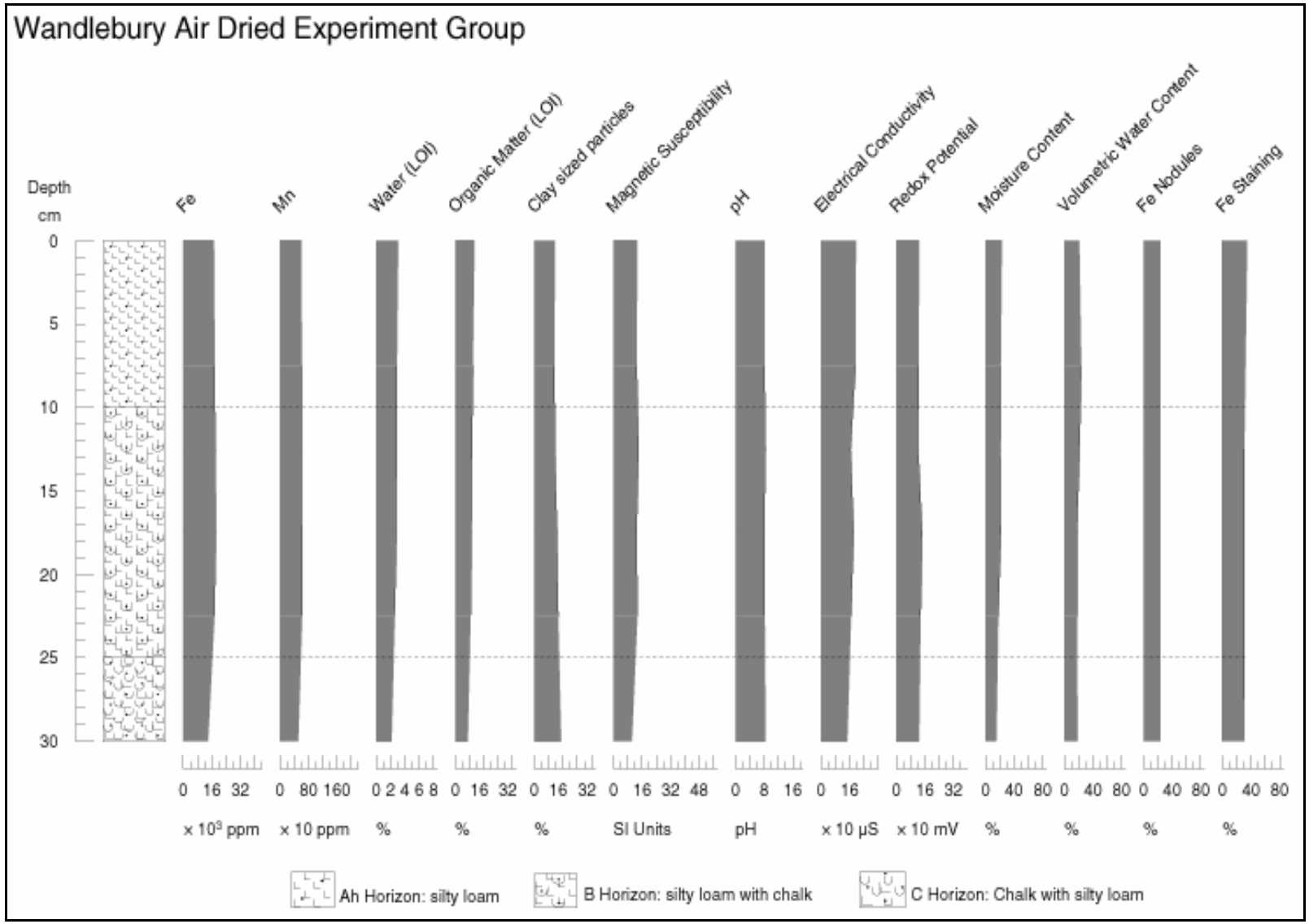


Figure 4.38. The comparative database (CDB) for the Wandlebury air dried experiment group.

The bulk analyses results for both the oven dried experiment group and the air dried experiment group are very similar with no significant differences. However, the two micromorphological variables, iron nodules and iron staining, have inverse relationships for each of the experiment groups. That is, the oven dried experiment group, representing the **rapid** introduction of oxygen into the soil environment, has a higher proportion of iron **nodules** to iron staining. However, the air dried experiment group, representing the **slow** introduction of oxygen into the soil environment, has a higher proportion of iron **staining** to iron nodules. Therefore, iron staining and iron nodules, as identified through soil micromorphology, are the most informative variables for identifying the oxidation processes within the soil environment. Although it is not clear if the decomposition of organic material was directly affected by the oxidation experiments at Wandlebury, I propose that given time these effects will be more clearly demarcated. However, there is another factor which will affect the organic material at this site, and that is the respiration and consumption activities of micro-organisms, particularly in reference to redox processes, as is evident from the prevalence of iron replacement. The deposition patterns of iron oxide in soils/sediments via microbial activity are ambiguous (cf. Fortin and Langley 2005). It is, therefore, difficult to know how this activity will influence the effectiveness of the CDB for deposits where microbial activity is present. In light of this, the inferences made from the application of the CDB for rendzinas must be considered with care, and therefore, some reservations.

4.4 SAVERNAKE

Savernake is an acidic argillic pelosol under an oak forest environment with a seasonally fluctuating groundwater table. The results of the bulk and soil micromorphological analyses (see table 3.1 in section 3.2) follow for each experiment group.

4.4.1 Bulk Analyses Data

A suite of bulk analyses were conducted on the oven dried and air dried bulk samples (see table 3.1 in section 3.2). Moisture content and VWC were recorded prior to the oxidation experiments and rainfall data was collected from Forestry Services. The results for each analysis for the oven dried group are presented here, followed by the results for the air dried group.

4.4.1.1 The Normal Curve and Seasonal Variation

The data for each analysis were tested for normal distribution by using a one-sampled K-S test (Field 2005). If the result is $p>.05$, then the data are deemed normally distributed. The results of this test for all the bulk analyses (oven dried group followed by air dried group) are presented in tables 4.12 and 4.13.

Table 4.12. Results of the normal distribution test for the oven dried group across all seasons. The value highlighted in bright blue indicates that this group is *not* normally distributed.

One-Sample Kolmogorov-Smirnov Test for Savernake Oven Dried Experiment Group

		Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox (mV)	Bulk Density (%)	Volumetric Water Content (%)
N		24	24	24	24	24	24	24	24	24	24	24
Normal Parameters[a,b]	Mean	35250.00	351.29	2.44	15.78	2.05	8.85	4.09	97.31	327.39	19.87	35.39
	Std. Deviation	7987.93	146.15	1.03	4.00	.51	5.36	.22	55.93	20.18	9.63	26.34
Most Extreme Differences	Absolute	.26	.14	.13	.11	.23	.25	.12	.29	.13	.13	.21
	Positive	.26	.14	.13	.11	.23	.25	.10	.29	.13	.07	.21
	Negative	-.16	-.10	-.07	-.11	-.13	-.18	-.12	-.23	-.10	-.13	-.16
Kolmogorov-Smirnov Z		1.26	.68	.64	.53	1.14	1.24	.60	1.43	.63	.62	1.02
Asymp. Sig. (2-tailed)		.08	.75	.80	.94	.15	.09	.87	.03	.83	.83	.24

a. Test distribution is Normal.

b. Calculated from data.

Table 4.13. Results of the normal distribution test for the air dried group across all seasons. The value highlighted in bright blue indicates that this group is *not* normally distributed.

One-Sample Kolmogorov-Smirnov Test for Savernake Air Dried Experiment Group

		Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox (mV)	Bulk Density (%)	Volumetric Water Content (%)
N		24	24	24	24	24	24	24	24	24	24	24
Normal Parameters[a,b]	Mean	41350.00	343.88	2.39	17.70	2.58	8.99	4.10	85.61	334.53	19.87	35.39
	Std. Deviation	9359.86	115.04	.83	3.70	.83	7.04	.14	35.52	17.97	9.63	26.34
Most Extreme Differences	Absolute	.15	.16	.17	.20	.27	.29	.16	.26	.19	.13	.21
	Positive	.15	.16	.17	.09	.27	.29	.08	.26	.19	.07	.21
	Negative	-.10	-.06	-.11	-.20	-.17	-.22	-.16	-.20	-.16	-.13	-.16
Kolmogorov-Smirnov Z		.74	.76	.85	.96	1.32	1.41	.76	1.27	.91	.62	1.02
Asymp. Sig. (2-tailed)		.65	.60	.46	.32	.06	.04	.61	.08	.38	.83	.24

a. Test distribution is Normal.

b. Calculated from data.

Data from the oven dried experiment group for Savernake are normally distributed except for the EC data. The data from the air dried experiment group for Savernake are normally distributed with the exception of %OM (LOI). In order to assess seasonal variability at Savernake, the means and standard errors were calculated for each bulk analysis and experiment group. The results are presented using bar graphs with error bars, as in figures 4.39 to 4.49 below.

Figures 4.39 to 4.47 represent seasonal variation for each of the bulk analyses for both the oven dried and the air dried experiment groups. Seasonal variation for Savernake is more apparent than the other sites, largely because of the impermeable nature of the soils and the seasonally fluctuating groundwater table. There are three variables that remain constant across seasons and oxidation experiment groups: %Clay, redox potential and pH (figures 4.43, 4.47 and 4.45). While there is seasonal variation for Fe, Mn, MS and EC, there is no significant variation between experiment groups (figures 4.39, 4.40, 4.44 and 4.46). This is expected as physical properties, such as these, are not likely to be affected by the oxidation experiments. Similarly, there does not appear to be any significant variability between experiment groups for %Water or %OM, with the exception of the 0-5cm samples in both cases (figures 4.41 and 4.42). These variables are slightly increased for the air dried experiment group (more so for %Water than %OM), which suggests that the clay and OM are holding more moisture in this group. As this material is more susceptible to holding in moisture than other more freely draining soils, the air dried samples may have absorbed atmospheric moisture. Whereas the oven dried samples were not exposed to atmospheric conditions, the air dried samples were exposed over a three month period in varying seasonal conditions. The variability of %OM between experiment groups and seasonal variability within experiment groups is smaller than %Water, and although every effort was made to ensure careful collection of the samples, the inclusion of some of the decomposing leaf litter in some of the samples may be the cause for the variability in %OM.

Seasonal variation for Fe and Mn is likely to be the result of the fluctuating groundwater table and subsequent redox processes. During periods of high groundwater table, the Fe and Mn are reduced and carried away in solution, while in periods of low groundwater table the Fe and Mn remain oxidised, and therefore, immobile. In addition, there appears to be greater variation in the upper, organic-rich horizon, which could be the result of decomposing organic material and the subsequent release of plant nutrients, including Fe and Mn. Further, there is a similar pattern of seasonal variation for MS (figure 4.44) and these results appear to reflect

more directly the patterns of Mn (figure 4.40) than Fe (figure 4.39), which suggests that the MS readings are more a reflection of Mn than Fe, suggesting that the Fe present at Savernake is not highly magnetic. This appears to be confirmed by the negative correlation between Fe and MS, as discussed further below.

The seasonal variation for %Water (figure 4.41) in both experiment groups is likely to be a result of the ability for clays to hold water: in wetter periods the soil will hold more water than in drier periods (see figures 2.11a and b in section 2.11.3). This pattern is also reflected in the results for moisture content (figure 4.48), VWC (figure 4.49), and EC (figure 4.46). As discussed in the previous chapter, EC is affected by soil type, moisture and organic material (Carroll and Oliver 2005). Clay-rich soils are more likely to hold moisture than sandy soils and the water holding capacity of organic material also affects the availability of soluble salts (*ibid*). Therefore, the similarities in patterns between EC, %Water and %OM are reasonable. Further, the lower EC values and decrease in variability towards the bottom of the profile could reflect the effects of the fluctuating groundwater table, carrying away the soluble salts in solution, effectively leaching the soil of these nutrients.

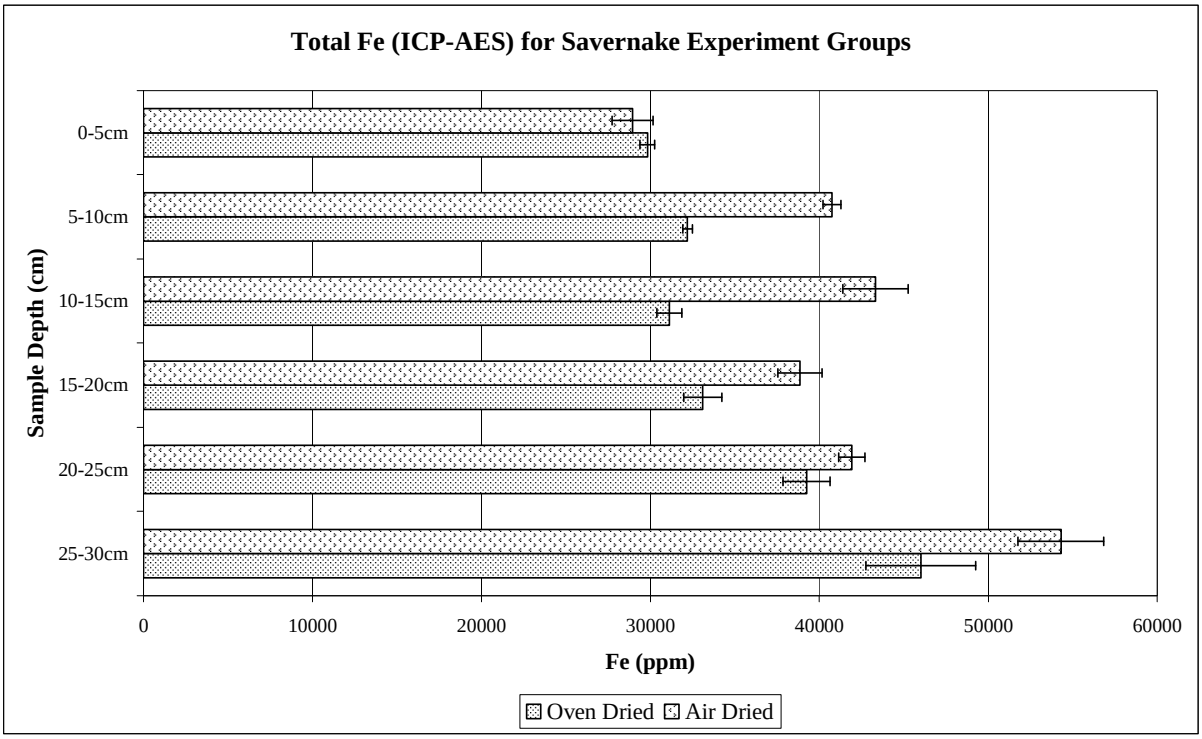


Figure 4.39. Mean and standard error for total Fe (ICP-AES) to determine seasonal variation for both the oven dried and air dried experiment groups.

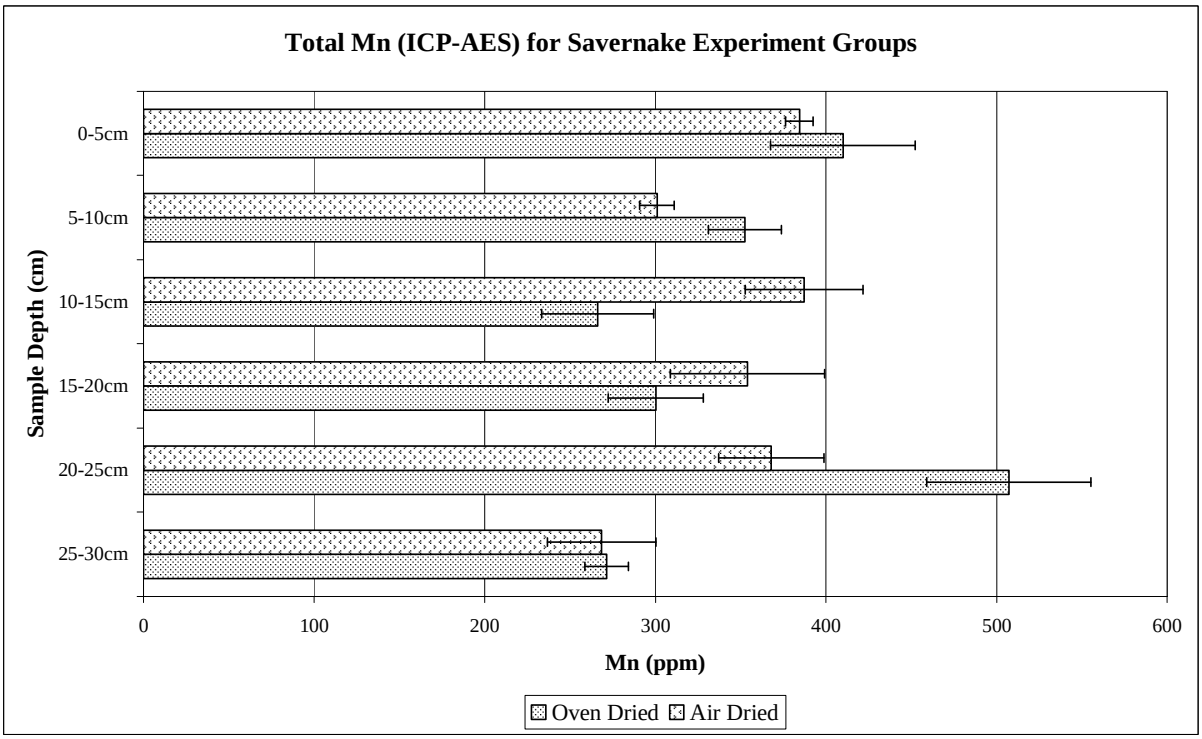


Figure 4.40. Mean and standard error for total Mn (ICP-AES) to determine seasonal variation for both the oven dried and air dried experiment groups.

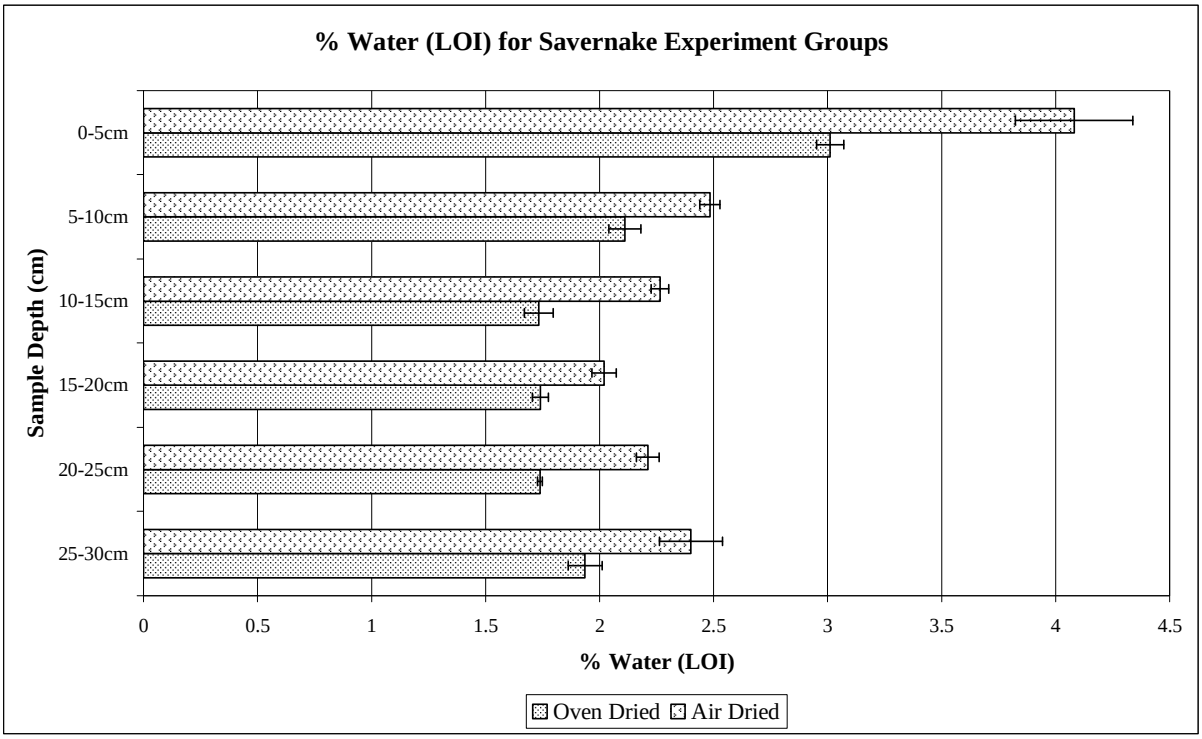


Figure 4.41. Mean and standard error for %Water (LOI) to determine seasonal variation for both the oven dried and air dried experiment groups.

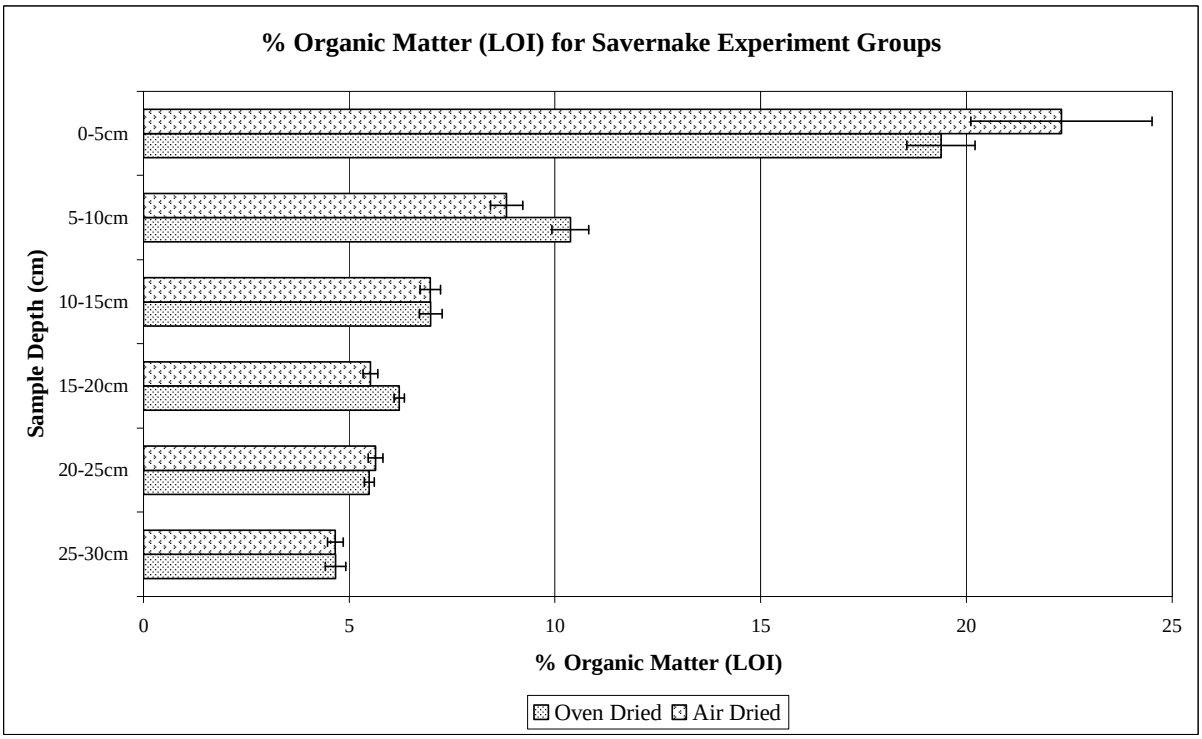


Figure 4.42. Mean and standard error for %Organic Matter (LOI) to determine seasonal variation for both the oven dried and air dried experiment groups.

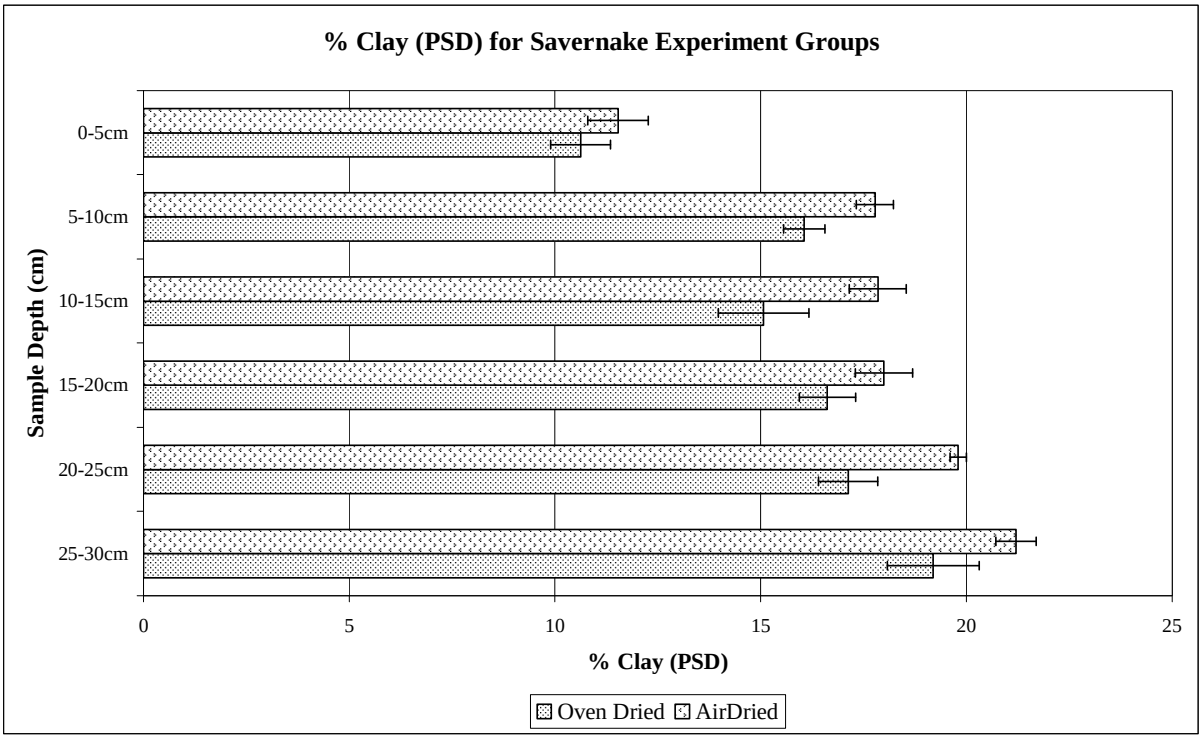


Figure 4.43. Mean and standard error for %Clay (PSD) to determine seasonal variation for both the oven dried and air dried experiment groups.

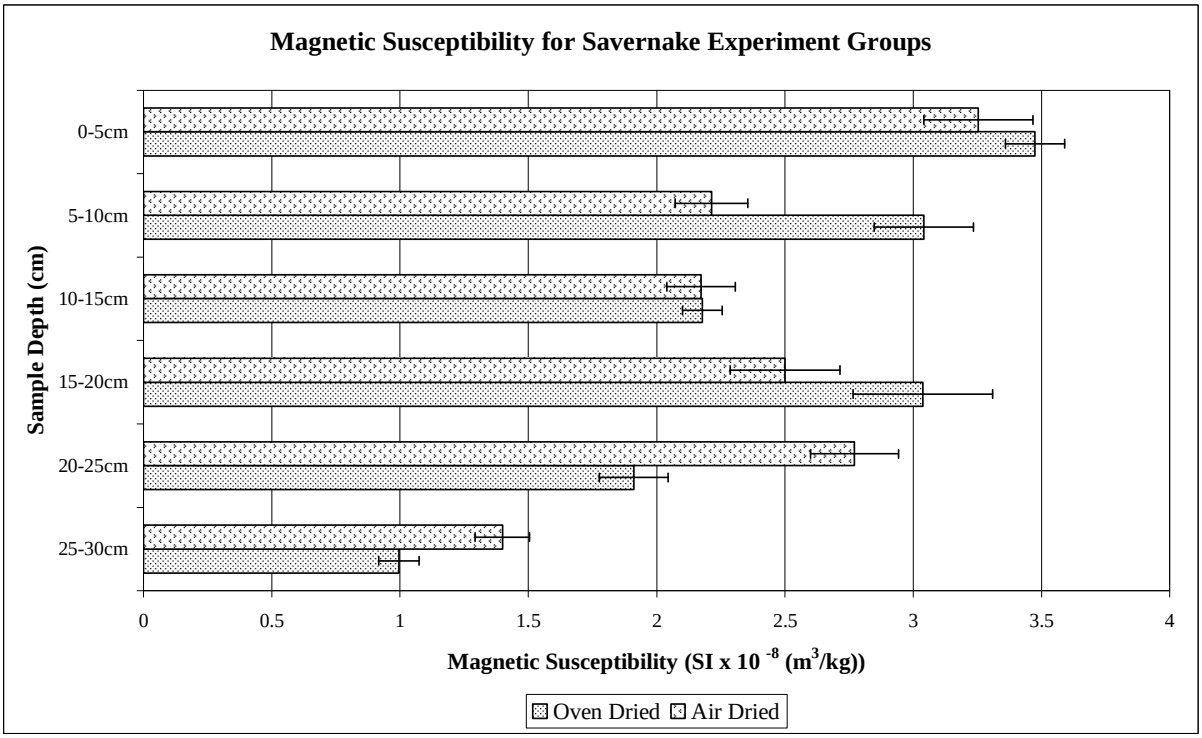


Figure 4.44. Mean and standard error for magnetic susceptibility to determine seasonal variation for both the oven dried and air dried experiment groups.

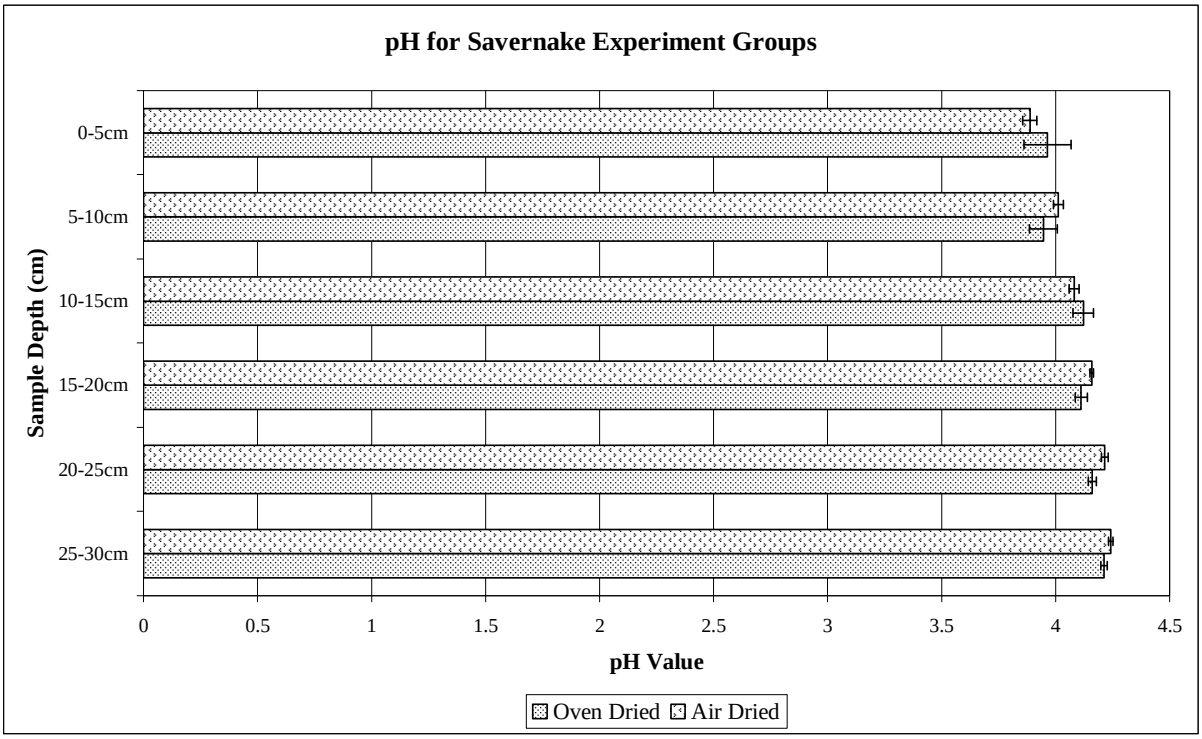


Figure 4.45. Mean and standard error for pH to determine seasonal variation for both the oven dried and air dried experiment groups.

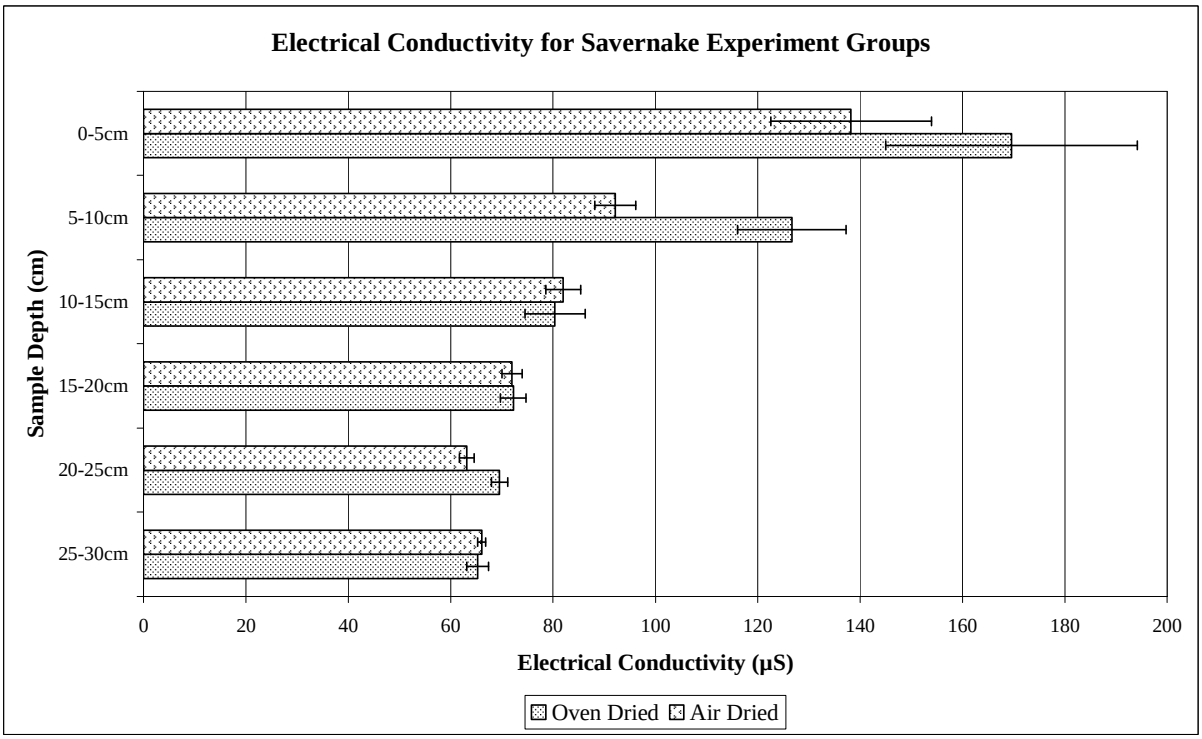


Figure 4.46. Mean and standard error for electrical conductivity to determine seasonal variation for both the oven dried and air dried experiment groups.

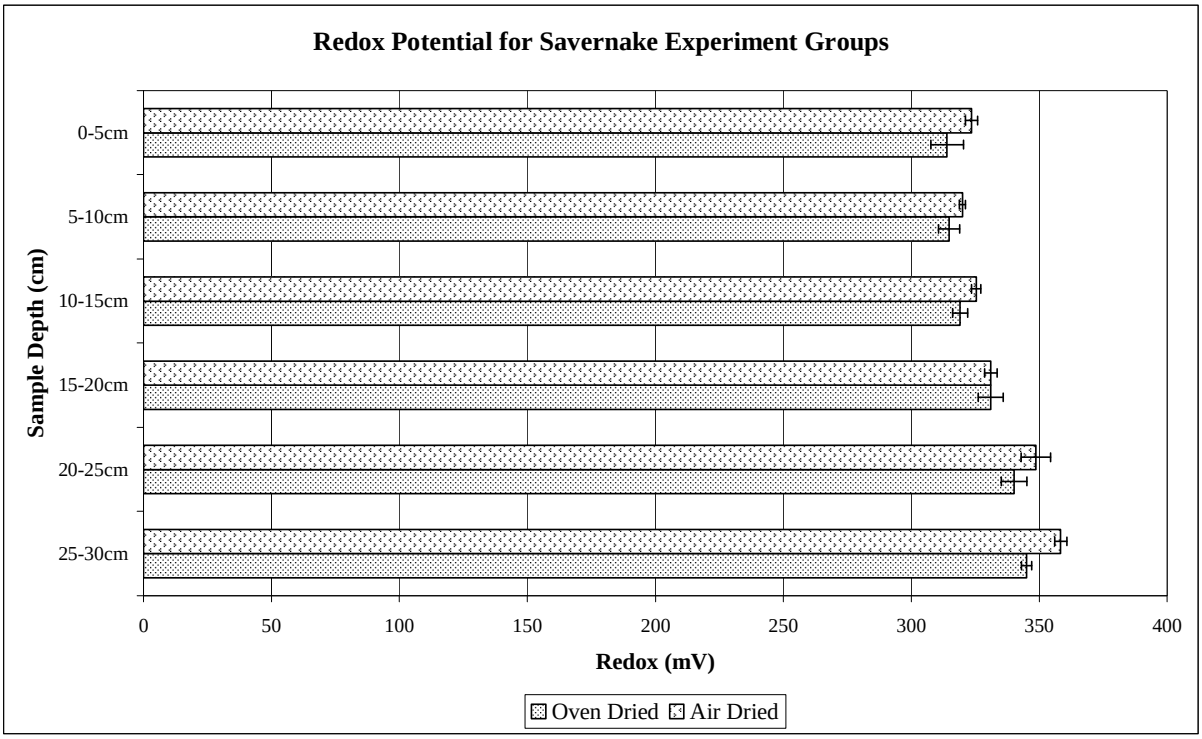


Figure 4.47. Mean and standard error for redox potential to determine seasonal variation for both the oven dried and air dried experiment groups.

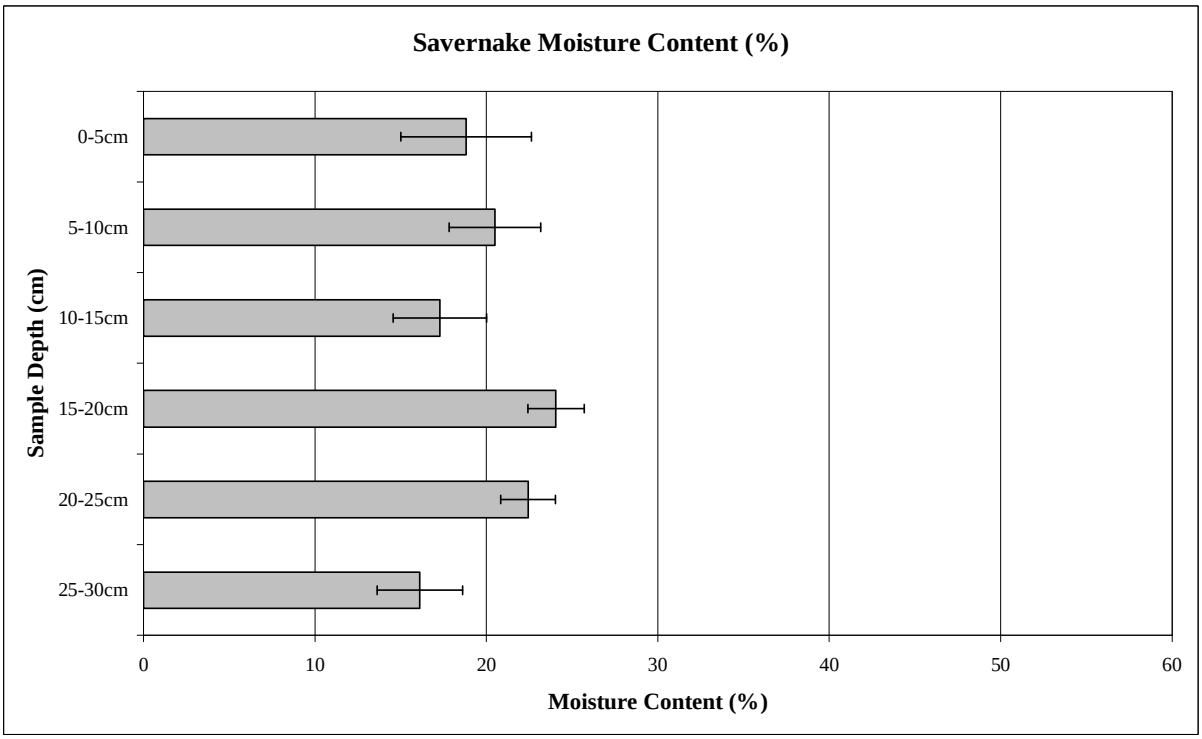


Figure 4.48. Mean and standard error to determine seasonal variation for the moisture content, taken prior to the oxidation experiments.

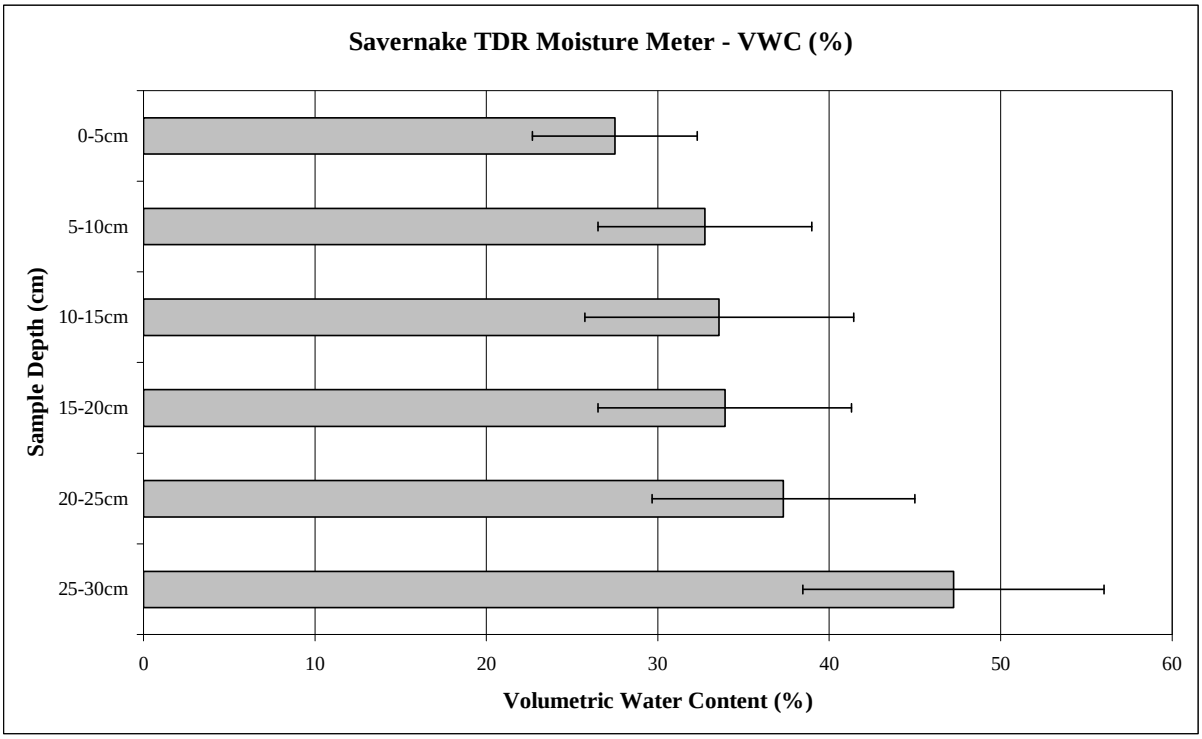


Figure 4.49. Mean and standard error to determine seasonal variation in soil moisture for the in-field measurements taken prior to sampling.

The results from the moisture content (figure 4.48), which is the percentage of moisture in the soil prior to the oxidation experiments, and the VWC from the in-field TDR moisture meter readings (figure 4.49) show more variation between seasons than the other bulk analyses data. This is expected as variation in rainfall will have a direct influence on the moisture readings for the soil. The rainfall records for the collection seasons show great variability with particularly dry seasons in autumn 2003 (which followed one of the driest summers on record in the UK) and summer 2004 (figure 4.50). Unfortunately, due to unforseen circumstances, the collection of rainfall data for Savernake over the spring of 2004 was not carried out (Tom Buchanan, Forestry Services, pers. comm.).

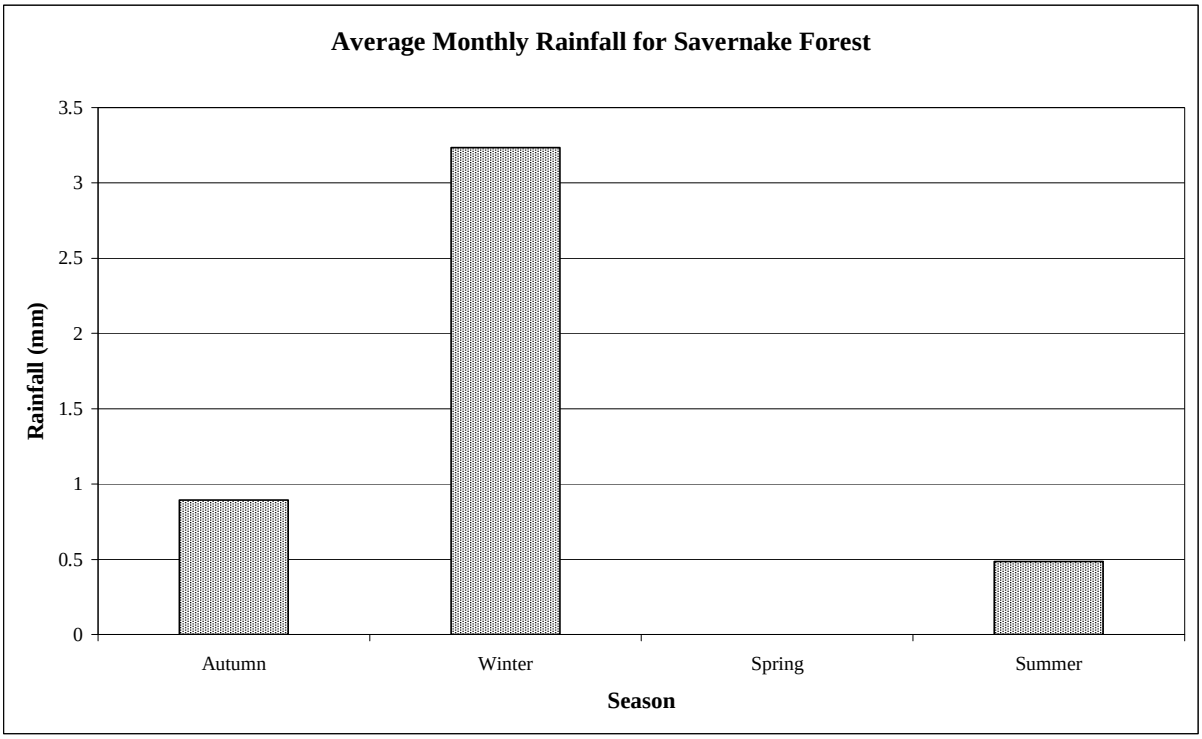


Figure 4.50. Total rainfall for Savernake from autumn 2003 to summer 2004 (October 2003, January, April and July, 2004). Unfortunately no data was collected for spring 2004 (data supplied by Forestry Services).

More curious for the moisture content and VWC results is the distinct difference between levels of moisture recorded from in-field readings and laboratory readings. This is possibly the result of the clay-rich, impermeable nature of the soils at Savernake. It is likely that in the field, the soils create pockets of water, which are trapped within the structure of the impermeable clay, and the probes from the moisture meter may have measured the moisture levels in these pockets. The moisture content readings were taken from samples collected in the field and the disturbance of the soil from this collection would have released any excess moisture trapped within the clay.

4.4.1.2 Correlation Coefficients and Relationships

As the data for both the oven dried experiment group and air dried experiment group for Savernake are not normally distributed (tables 4.12 and 4.13), Spearman's rho correlation coefficient was used to highlight relationships between the different analytical variables (Field 2005). Although relationships between variables were expected, the direction of the relationships was not predicted; therefore, a two-tailed significance test was used (*ibid*). These results are presented in tables 4.14 and 4.15 below.

Table 4.14. Spearman's rho correlation was used for the Savernake oven dried experiment group as the data are not normally distributed. Significant correlations are highlighted.

Correlations for Savernake Oven Dried Experiment Group

			Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox (mV)	Bulk Density (%)	Volumetric Water Content (%)
Spearman's rho	Fe (ppm)	Correlation Coefficient	1.000	.428*	-.468*	.668**	-.508*	-.719**	.429*	-.599**	.630**	.007	.085
		Sig. (2-tailed)	.	.037	.021	.000	.011	.000	.037	.002	.001	.976	.693
		N	24	24	24	24	24	24	24	24	24	24	24
	Mn (ppm)	Correlation Coefficient	.428*	1.000	.164	.207	-.027	.088	-.042	.049	.316	.229	-.063
		Sig. (2-tailed)	.037	.	.444	.331	.900	.682	.846	.820	.133	.282	.771
		N	24	24	24	24	24	24	24	24	24	24	24
	Magnetic Susceptibility (SI Units)	Correlation Coefficient	-.468*	.164	1.000	-.291	.414*	.776**	-.169	.404	-.539**	-.140	-.542**
		Sig. (2-tailed)	.021	.444	.	.167	.044	.000	.431	.050	.007	.514	.006
		N	24	24	24	24	24	24	24	24	24	24	24
	% Clay (PSD)	Correlation Coefficient	.668**	.207	-.291	1.000	-.341	-.430*	.170	-.376	.285	-.061	-.035
		Sig. (2-tailed)	.000	.331	.167	.	.103	.036	.428	.070	.177	.778	.872
		N	24	24	24	24	24	24	24	24	24	24	24
	% Water (LOI)	Correlation Coefficient	-.508*	-.027	.414*	-.341	1.000	.754**	-.367	.704**	-.302	-.195	-.130
		Sig. (2-tailed)	.011	.900	.044	.103	.	.000	.078	.000	.152	.362	.545
		N	24	24	24	24	24	24	24	24	24	24	24
	% Organic Matter (LOI)	Correlation Coefficient	-.719**	.088	.776**	-.430*	.754**	1.000	-.503*	.769**	-.545**	-.072	-.292
		Sig. (2-tailed)	.000	.682	.000	.036	.000	.	.012	.000	.006	.738	.166
		N	24	24	24	24	24	24	24	24	24	24	24
	pH Value	Correlation Coefficient	.429*	-.042	-.169	.170	-.367	-.503*	1.000	-.690**	-.117	-.579**	-.532**
		Sig. (2-tailed)	.037	.846	.431	.428	.078	.012	.	.000	.585	.003	.007
		N	24	24	24	24	24	24	24	24	24	24	24
	Electrical Conductivity (µS)	Correlation Coefficient	-.599**	.049	.404	-.376	.704**	.769**	-.690**	1.000	-.209	.274	.187
		Sig. (2-tailed)	.002	.820	.050	.070	.000	.000	.000	.	.327	.195	.383
		N	24	24	24	24	24	24	24	24	24	24	24
	Redox (mV)	Correlation Coefficient	.630**	.316	-.539**	.285	-.302	-.545**	-.117	-.209	1.000	.410*	.553**
		Sig. (2-tailed)	.001	.133	.007	.177	.152	.006	.585	.327	.	.047	.005
		N	24	24	24	24	24	24	24	24	24	24	24
	Bulk Density (%)	Correlation Coefficient	.007	.229	-.140	-.061	-.195	-.072	-.579**	.274	.410*	1.000	.694**
		Sig. (2-tailed)	.976	.282	.514	.778	.362	.738	.003	.195	.047	.	.000
		N	24	24	24	24	24	24	24	24	24	24	24
	Volumetric Water Content (%)	Correlation Coefficient	.085	-.063	-.542**	-.035	-.130	-.292	-.532**	.187	.553**	.694**	1.000
		Sig. (2-tailed)	.693	.771	.006	.872	.545	.166	.007	.383	.005	.000	.
		N	24	24	24	24	24	24	24	24	24	24	24

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

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

Correlations with significance levels of $p<.05$ and $p<.01$ are marked by asterisks in each of the correlation tables. I will first discuss the correlations for the oven dried experiment group, followed by the air dried experiment group for Savernake.

In the oven dried experiment group (table 4.14) there are several correlations between Fe and other variables, including Mn ($r_s = .428$, $p<.05$), MS ($r_s = -.468$, $p<.05$), %Clay ($r_s = .668$, $p<.0001$), %Water ($r_s = -.508$, $p<.05$), %OM ($r_s = -.719$, $p<.0001$), pH ($r_s = .429$, $p<.05$), redox ($r_s = .630$, $p<.001$), and EC ($r_s = -.599$, $p<.01$). The positive correlation between Fe and Mn is expected as these minerals are often associated with each other and behave in similar ways. The negative correlation between Fe and MS indicates that the Fe present in the soils at Savernake does not necessarily have magnetic properties. It is possible that the MS readings are influenced by other magnetically susceptible minerals, such as Mn (Coey 1988). However, there is no significant correlation between Mn and MS, which suggests that other minerals may be contributing to the readings, such as copper and cobalt, which are associated with plant material (appendix G, table G-3). The relationship between Fe and %Clay is expected as Fe often combines with clay and can travel through the soil profile via illuviation processes. This is supported by the presence of iron-rich clay coatings of grains and voids increasing down profile, as identified by the soil micromorphological analyses below. The negative correlation between Fe and %Water may be the result of redox processes with Fe being carried away with the fluctuating groundwater table. Conversely, with lower levels of water present in the soil, the iron oxidises and becomes immobile, thereby resulting in higher levels of Fe and a lower percentage of water. The negative correlation between %OM and Fe suggests a small quantity of Fe in the soil is originating from the decomposition of OM, which supports the high quantities of OM present in the 0-5cm samples and the proportionately low quantity of OM in the lower soil horizons. This pattern is further supported by the soil micromorphological analyses below.

The negative correlation between Fe and EC reflects the relationship between %Water and Fe, suggesting that a large portion of soluble salts is being leached from the soil with the natural fluctuations of the groundwater table. Further, the pattern of distribution for EC reflects this with a decrease in EC down profile. Likewise, the positive correlation between redox and Fe suggests that the deposition of Fe is largely dependent on redox processes and the associated fluctuations of the groundwater table, which are responsible for the iron oxidation at Savernake. The final correlation with Fe is pH, and relative to the range of pH (3.6-4.6), the

positive correlation between these variables is expected, as acidic conditions are conducive to high quantities of Fe in the soil (Loeppert and Inskeep 1996).

The positive correlation between MS and %OM (r_s = .776, p<.0001) suggests that the source of the MS readings is more likely to be the decomposition of OM in the soil than other minerals, such as Fe and Mn, indicating that other magnetic plant minerals may be contributing to the MS of the soils at Savernake. However, the positive correlation between MS and %Water (r_s = .414, p<.05) remains unclear, and is perhaps more a reflection of the similarities in the distribution pattern down the soil profile for the two variables. The negative correlation between MS and redox (r_s = -.539, p<.01) supports the idea that the MS readings are not associated with deposition of Fe and Mn via redox processes. The negative correlation between MS and VWC (r_s = -.542, p<.01) remains unclear, and similar to %Water, this correlation is most likely a representation of the pattern of distribution for each of the variables.

The negative correlation between %Clay and %OM (r_s = -.430, p<.05) reflects the idea that there is a larger quantity of clay present in the soil than OM, which supports that the majority of Fe and Mn present in the soil is originating from the clay component of the soil and the associated redox processes, as opposed to the decomposition of OM. The positive correlations between %Water and %OM (r_s = .754, p<.0001) and %Water and EC (r_s = .704, p<.0001) suggest that the OM is retaining some of the moisture after the oxidation experiment, and the relationship between %Water and EC is expected, as any soluble salts available will be retained in the moisture content of the soil. The positive correlation between EC and %OM (r_s = .769, p<.0001) further supports the inference that moisture is trapped within the organic component of the soil. There is a negative correlation between pH and %OM, which is expected as the decomposition of OM and the subsequent release of natural acids causes an increase in the acidity of the soil, i.e. the higher the organic content, the lower the pH. The strong negative correlation between redox and %OM (r_s = -.545, p<.01) suggests that the more oxidised the environment, the lower the quantity of OM. As the redox potential for Savernake shows highly oxidised conditions, this relationship is expected as oxygen is a key factor in the decomposition of OM.

The negative correlations between pH and moisture content (r_s = -.579, p<.01) and between pH and VWC (r_s = -.532, p<.01) reflect the acidity of the soil and the high levels of moisture

Table 4.15. Spearman's rho correlation was used for the Savernake air dried experiment group as the data are not normally distributed. Significant correlations are highlighted.

Correlations for Savernake Air Dried Experiment Group

			Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox (mV)	Bulk Density (%)	Volumetric Water Content (%)
Spearman's rho	Fe (ppm)	Correlation Coefficient	1.000	-.295	-.622**	.808**	-.290	-.517**	.627**	-.432*	.363	-.122	.042
		Sig. (2-tailed)	.	.162	.001	.000	.169	.010	.001	.035	.081	.569	.844
		N	24	24	24	24	24	24	24	24	24	24	24
	Mn (ppm)	Correlation Coefficient	-.295	1.000	.277	-.346	.118	.165	-.368	.053	-.038	-.013	-.088
		Sig. (2-tailed)	.162	.	.189	.098	.582	.440	.077	.804	.859	.952	.682
		N	24	24	24	24	24	24	24	24	24	24	24
	Magnetic Susceptibility (SI Units)	Correlation Coefficient	-.622**	.277	1.000	-.564**	.260	.435*	-.320	.122	-.495*	-.031	-.343
		Sig. (2-tailed)	.001	.189	.	.004	.220	.034	.128	.569	.014	.885	.101
		N	24	24	24	24	24	24	24	24	24	24	24
	% Clay (PSD)	Correlation Coefficient	.808**	-.346	-.564**	1.000	-.286	-.611**	.699**	-.528**	.412*	.029	.113
		Sig. (2-tailed)	.000	.098	.004	.	.175	.002	.000	.008	.045	.894	.600
		N	24	24	24	24	24	24	24	24	24	24	24
	% Water (LOI)	Correlation Coefficient	-.290	.118	.260	-.286	1.000	.757**	-.594**	.546**	-.312	-.319	-.187
		Sig. (2-tailed)	.169	.582	.220	.175	.	.000	.002	.006	.138	.129	.381
		N	24	24	24	24	24	24	24	24	24	24	24
	% Organic Matter (LOI)	Correlation Coefficient	-.517**	.165	.435*	-.611**	.757**	1.000	-.839**	.718**	-.641**	-.077	-.155
		Sig. (2-tailed)	.010	.440	.034	.002	.000	.	.000	.000	.001	.722	.469
		N	24	24	24	24	24	24	24	24	24	24	24
	pH Value	Correlation Coefficient	.627**	-.368	-.320	.699**	-.594**	-.839**	1.000	-.871**	.433*	-.177	-.094
		Sig. (2-tailed)	.001	.077	.128	.000	.002	.000	.	.000	.034	.408	.662
		N	24	24	24	24	24	24	24	24	24	24	24
	Electrical Conductivity (µS)	Correlation Coefficient	-.432*	.053	.122	-.528**	.546**	.718**	-.871**	1.000	-.271	.223	.191
		Sig. (2-tailed)	.035	.804	.569	.008	.006	.000	.000	.	.199	.296	.372
		N	24	24	24	24	24	24	24	24	24	24	24
	Redox (mV)	Correlation Coefficient	.363	-.038	-.495*	.412*	-.312	-.641**	.433*	-.271	1.000	.246	.507*
		Sig. (2-tailed)	.081	.859	.014	.045	.138	.001	.034	.199	.	.246	.012
		N	24	24	24	24	24	24	24	24	24	24	24
	Bulk Density (%)	Correlation Coefficient	-.122	-.013	-.031	.029	-.319	-.077	-.177	.223	.246	1.000	.694**
		Sig. (2-tailed)	.569	.952	.885	.894	.129	.722	.408	.296	.246	.	.000
		N	24	24	24	24	24	24	24	24	24	24	24
	Volumetric Water Content (%)	Correlation Coefficient	.042	-.088	-.343	.113	-.187	-.155	-.094	.191	.507*	.694**	1.000
		Sig. (2-tailed)	.844	.682	.101	.600	.381	.469	.662	.372	.012	.000	.
		N	24	24	24	24	24	24	24	24	24	24	24

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

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

in the soils prior to the oxidation experiment. In addition, the relationship between EC and pH (r_s = -.690, p<.0001) reflects the acidity of the soil and the availability of soluble salts through the high moisture levels in the soil. Finally, the positive correlations between redox and moisture content (r_s = .410, p<.05) and redox and VWC (r_s = .553, p<.01) suggest that redox processes in the soils at Savernake are directly influenced by water content, supporting cycles of reducing and oxidising conditions in relation to the seasonal fluctuations of the groundwater table.

The correlations of Fe with other variables in the air dried experiment group (table 4.15) are similar to the correlations in the oven dried experiment group. These include Fe and MS (r_s = -.622, p<.001), Fe and %Clay (r_s = .808, p<.0001), Fe and %OM (r_s = -.517, p<.01), Fe and pH (r_s = .627, p<.001), and Fe and EC (r_s = -.432, p<.05). Similar to the oven dried experiment group, the negative correlation between Fe and MS for the air dried experiment group indicates that there is no magnetically susceptible Fe present in the soils at Savernake (see appendix G, table G-3 for other contributors to the MS readings). Also, the relationship between Fe and %Clay is expected as Fe often combines with clay and can travel through the soil profile via illuviation processes, which is further supported by the increasing presence of iron-rich clay coatings of voids and grains down profile, as identified by the soil micromorphological analyses below. Further, the negative correlation between %OM and Fe suggests a small quantity of Fe in the soil is originating from the decomposition of OM, which supports the high quantities of OM present in the 0-5cm samples and the proportionately low quantity of OM in the lower soil horizons. The positive correlation between Fe and pH is expected, as relative to the range of pH (3.6-4.6), the acidic conditions are conducive to high quantities of Fe in the soil. The negative correlation between Fe and EC remains unclear, as unlike the oven dried experiment group, there is no relationship between Fe and %Water or any other measure of soil moisture. However, the correlation between %Water and %OM (r_s = .757, p<.0001) suggests that the available water is held within the organic component of the soil, and given the correlation of Fe with %OM, it is possible that the correlation of Fe with EC is reflecting this relationship.

The negative correlation between MS and %Clay (r_s = -.564, p<.01) supports the idea that the magnetically susceptible minerals are not part of the clay component of the soil but are more likely to be originating from the breakdown of OM, than from redox processes via the fluctuating groundwater table. This is further confirmed by the positive correlation of MS with %OM (r_s = .435, p<.05). In addition, the negative correlation between MS and redox

(r_s = -.495, p<.05) reflects the relationship between Fe and MS, in that redox processes are responsible for the deposition of Fe in the soil at Savernake but that this Fe deposition is not magnetically susceptible.

There are several correlations between %Clay and other variables, such as %OM (r_s = -.611, p<.01), pH (r_s = .699, p<.0001), EC (r_s = -.528, p<.01) and redox (r_s = .412, p<.05). The negative correlation between %Clay and %OM reflects the idea that there is a larger quantity of clay present in the soil than OM, which is in agreement with the oven dried experiment group, and suggests that the majority of Fe and Mn present in the soil is originating from the clay component of the soil and the associated redox processes, rather than from the decomposition of OM. Relative to the acidic range at Savernake, the positive correlation between pH and %Clay is expected as Savernake is both rich in clay and acidity. The positive correlation between %Clay and EC suggests that some moisture is being retained within the clay fabric of the soil, thereby trapping available soluble salts. This result is expected as clays are known to be more conducive to such conditions than more sandy soils (Carroll and Oliver 2005). This further suggests that the air dried samples are retaining more moisture in the clay component of the soil than the oven dried samples, and is supported in the variations in soil porosity in the soil micromorphological analyses below. The positive relationship between %Clay and redox suggests that clay plays an important role in redox processes, i.e. clays are conducive to reducing and oxidising cycles and Fe, in its soluble form, bonds well with clay when oxidised (Limbrey 1975; Loeppert and Inskeep 1996).

The negative relationship between %Water and pH (r_s = -.594, p<.01) is expected as the site is acidic and the impermeable nature of the soil is conducive to water retention, even under oxidising conditions. Further, the variation in atmospheric moisture during the air drying of the soils could have affected the moisture content of the soils more so than for the oven dried experiment group. The positive correlation between %Water and EC (r_s = .546, p<.01) is expected as EC is a measure of the available soluble salts, which are retained in the water content of the soil. In addition, the negative correlation between EC and pH (r_s = -.871, p<.0001) reflects that of %Water and pH and EC and %Water, suggesting free availability of soluble salts and the acidity of the soil environment.

The negative correlation between %OM and pH (r_s = -.839, p<.0001) is expected as the site is acidic and an increase in OM can, in turn, increase the acidity of the soil environment. The relationship between %OM and EC (r_s = .718, p<.0001) is expected as moisture can be

retained within the organic component of the soil and EC is known to be affected by the soil OM content (Carroll and Oliver 2005). Similar to the oven dried experiment group, the negative correlation between %OM and redox (r_s = -.641, p<.001) supports the relationship between Fe and %OM and suggests that the role of OM in the redox processes at Savernake is minimal, and that the redox processes that are occurring are more likely to be the result of the fluctuating groundwater table. The positive relationship between pH and redox (r_s = .433, p<.05) suggests that relative to the pH range of the site, the soils at Savernake are conducive to redox processes. Further, the positive correlation between redox and VWC (r_s = .507, p<.05) lends support to the occurrence of reducing and oxidising conditions in relation to fluctuating groundwater levels.

The correlation between moisture content and VWC (r_s = .694, p<.0001) is present in tables 4.14 and 4.15. The correlations in these tables are identical as they were taken as a control for the moisture in the soil prior to the drying out experiments. The strong positive correlation between these variables confirms the accuracy of both methods: moisture content is a measure of soil moisture before drying out, and is as close to in-field moisture levels as possible in a laboratory environment, and VWC is a direct in-field reading of the soil moisture content at Savernake.

Finally, the lack of correlation of Mn with any other variables in the air dried experiment group, and with only one correlation with Fe in the oven dried experiment group, suggests that Mn plays a minor role in the soil formation processes at Savernake, in spite of its presence in large quantities, especially with regard to the seasonally fluctuating groundwater levels and consequent redox processes.

4.4.2 Soil Micromorphology

Soil micromorphological analyses were carried out for each experiment group: oven dried, air dried and control, with particular focus on microstructure, relative porosity, iron oxide deposition, and organic material (appendix F). The descriptions follow Bullock *et al.* (1985) and Stoops (2003) and the coarse-fine limit for the soils at Savernake is set at 20µm. I will first provide a brief description of the soil microstructure and porosity, followed by more detail on iron oxide deposition and organic material.

4.4.2.1 Microstructure and Porosity

The fine fraction of the soils at Savernake is iron-rich silty clay with an organic-rich A horizon. The granular to crumb structure of the A horizon suggests that some bioturbation and organic decomposition is occurring, which is supported by the presence of mite excrement (appendix F). The dominance of channel voids in the lower horizons suggests the presence of roots and rootlets, and the subrounded blocky structure is the result of shrink-swell activity, common in clays with a fluctuating groundwater table.

The dominance of the fine material, such as clay, at Savernake is supported by the single spaced porphyric distribution and coarse-fine ratio of 2:3. The fine material in the A horizon is predominantly stipple speckled with some areas masked by humic material. The B horizon is generally stipple speckled with oriented clay coatings of grains and voids and occasionally some randomly striated clay zones. The B/C horizon is dominated by randomly striated clay zones and oriented clay coatings of grains and voids. These clay coatings are the result of illuviation, suggesting that clay is moving from the upper horizon and being deposited in the lower B and B/C horizons, a process which is expected in such a clay-rich soil environment.

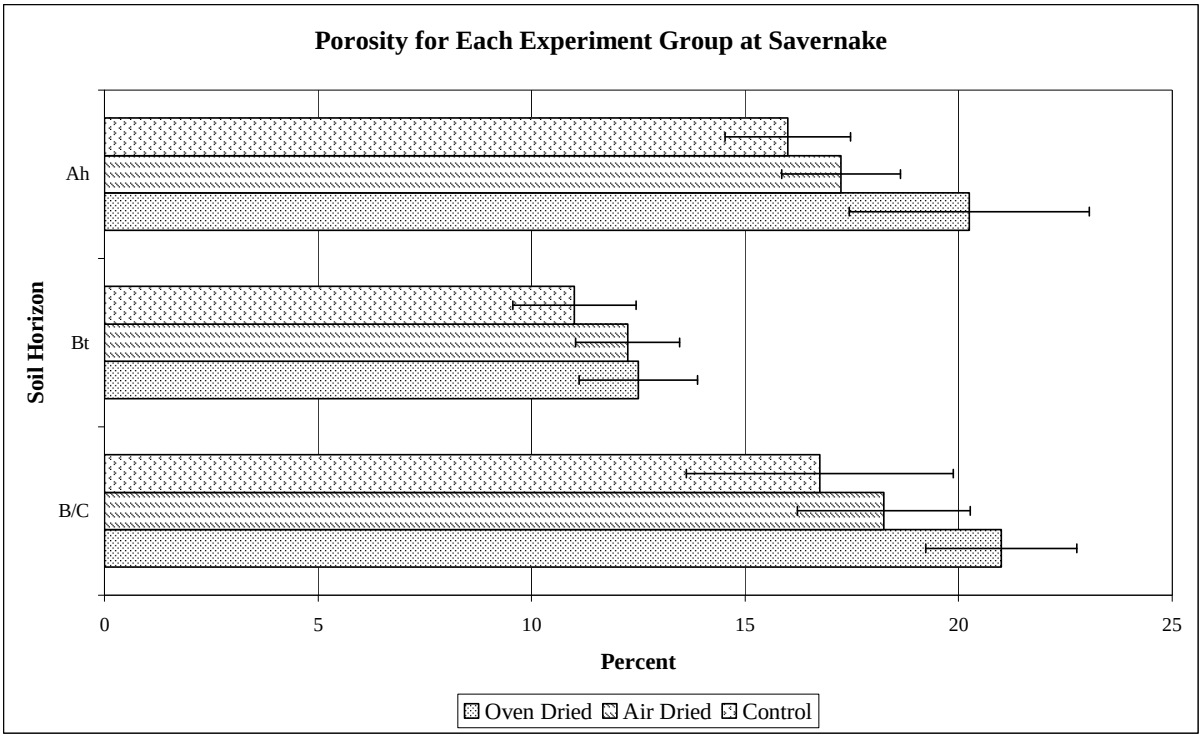


Figure 4.51. Mean porosity (%) and seasonal variation (error bars) for the soils at Savernake for all experiment groups.

Figure 4.51 presents the mean porosity for each experiment group for Savernake, along with the seasonal variation. The first interesting result is the distinct differences in porosity for

each of the experiment groups. The control group, representative of *in situ* conditions for the soil environment at Savernake, has the least percentage of soil porosity. There is significant seasonal variation, which is expected due to the variation in both rainfall and the natural fluctuations of the groundwater table. The air dried experiment group lies midway between the control and oven dried experiment, again with significant seasonal variation, reflecting the level of moisture retained in the clay-rich soil following the oxidation experiment. Finally, the oven dried experiment group has the greatest porosity with similar seasonal variation to the other two groups. Consequently, it seems that the rapid oxidation experiment has had the most significant effect on the porosity of the soil at Savernake. Further, the slow oxidation experiment has increased soil porosity, although the variation for this group lies more clearly within the percentages for the control group, whereas the oven dried experiment group is not as closely related to the control group. Therefore, I suggest that rapid oxidation has a greater effect on the soil environment than slow oxidation.

4.4.2.2 Iron Oxide Deposition

The iron oxide deposition present at Savernake includes nodules, staining, replacement of organic material and coatings of grains and voids. There are no pans present in the soil at Savernake. Figure 4.52 shows there is some variation in the percentage of iron coatings between the different experiment groups, in addition to seasonal variation. Iron-rich clay coatings are the result of illuviation processes and are affected by variations in rainfall, and in the case of Savernake, fluctuations in the groundwater table. Further, the distribution of coatings down the soil profile suggests that illuviation is an active process at Savernake with a definite increase in coatings in the lower horizons of the soil profile.

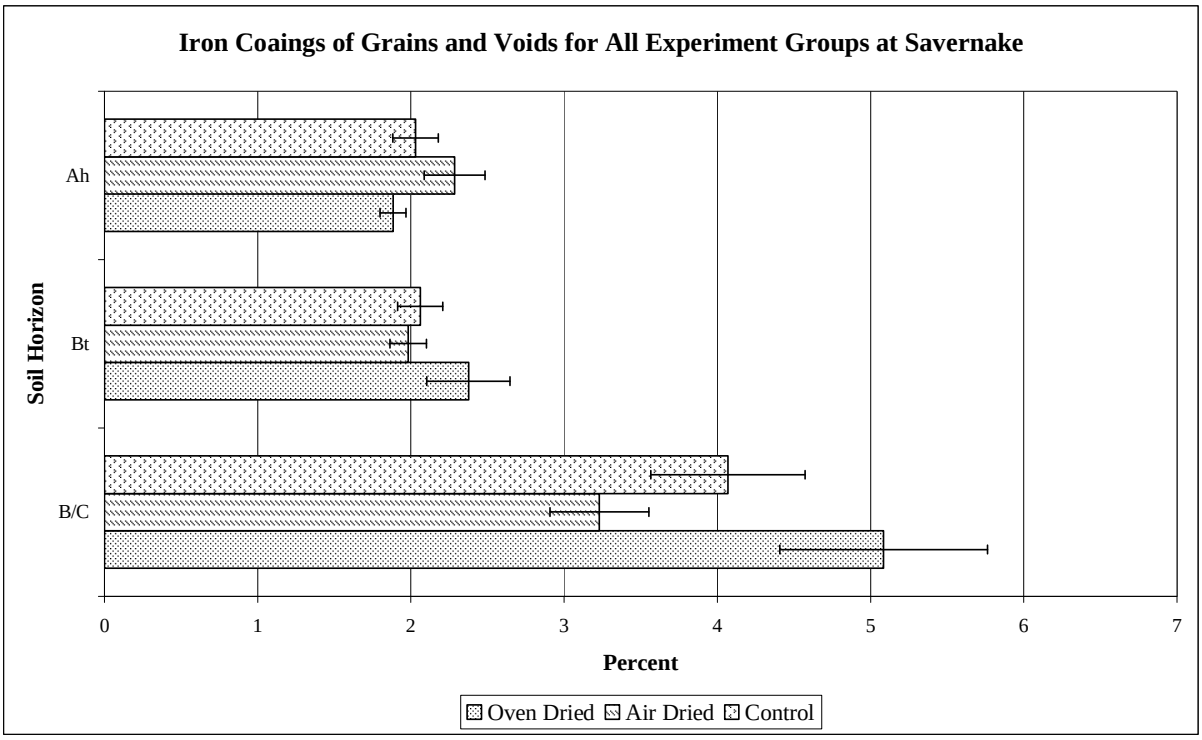


Figure 4.52. Mean percentage of coatings and seasonal variation (error bars) for all experiment groups at Savernake.

The replacement of organic material by iron oxide is prevalent in the soil environment at Savernake (table 4.16) and predominant in the A and B soil horizons. The presence of iron replacement in the A horizon could be the result of microbial activity causing reducing-oxidising cycles, while the iron replacement in the B and B/C horizons is more likely the result of redox processes by way of the fluctuating groundwater table. There does not appear to be any significant differences between the experiment groups or seasons, although there is a slight increase in replacement during winter and spring when the groundwater table is at its highest.

Table 4.16. Results for the percentage of iron replacement of organic matter, as identified through soil micromorphological analysis.

Sample Number		Soil Horizon	Replacement		
			Frequency	Minimum (µm)	Maximum (µm)
October 2003	**1.1**	Ah	■■■■	110	788
	1.2	Bt	■■■	94	290
	1.3	B/C	■	100	283
	2.1	Ah	■	200	307
	2.2	Bt	■■	105	258
	2.3	B/C	■	175	450
	3.1	Ah	■	95	343
	3.2	Bt	■	173	373
	3.3	B/C	■	450	450
January 2004	**1.1**	Ah	■■	83	450
	1.2	Bt	■■	90	210
	1.3	B/C	■■	83	467
	2.1	Ah	■■■	97	327
	2.2	Bt	■■■■	103	702
	2.3	B/C	■■■	126	432
	3.1	Ah	■■■	106	694
	3.2	Bt	■■■	108	410
	3.3	B/C	■	150	373
April 2004	**1.1**	Ah	■■■	124	546
	1.2	Bt	■	83	243
	1.3	B/C	■	193	300
	2.1	Ah	■■■	183	792
	2.2	Bt	■■■	125	517
	2.3	B/C	■	175	263
	3.1	Ah	■■	228	420
	3.2	Bt	■■	120	350
	3.3	B/C	■■■	184	414
July 2004	**1.1**	Ah	■■■	76	680
	1.2	Bt	■■	130	458
	1.3	B/C	■	233	500
	2.1	Ah	■■■	110	454
	2.2	Bt	■■	220	490
	2.3	B/C	■	200	200
	3.1	Ah	■■■	144	394
	3.2	Bt	■■	140	240
	3.3	B/C	■	140	533

Key: ■ <2%, ■■ 2-5%, ■■■ 5-10%, ■■■■ 10-20%, ■■■■■ 20-30%, ■■■■■■ 30-40%, ■■■■■■■ 40-50%, ■■■■■■■■ 50-60%, ■■■■■■■■■ 60-70%

While iron coatings and replacement of organic material by iron oxide are not likely to be affected by the oxidation experiments, but are instead indicators of the soil environment at Savernake, iron nodules and iron staining are two deposition types that are expected to be altered by the experiments.

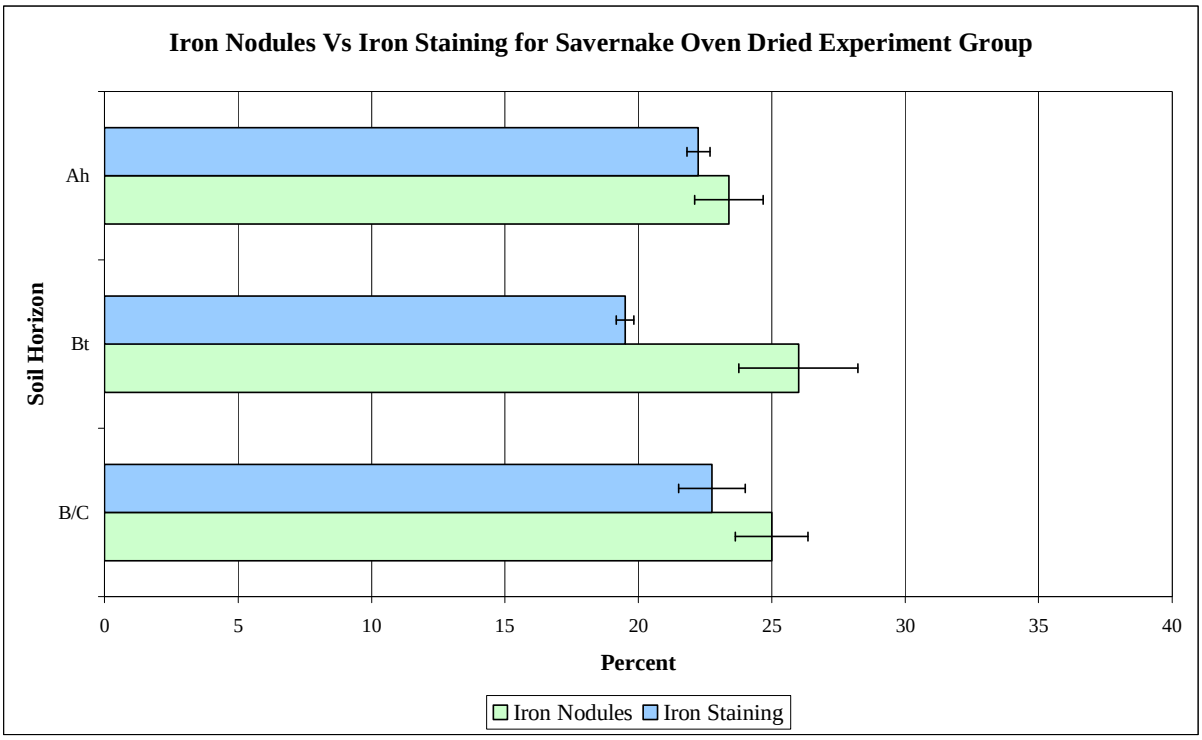


Figure 4.53. Mean percentage of iron nodules and iron staining, and the seasonal variation (error bars) for the oven dried experiment group at Savernake.

The results of the oven dried experiment group show that iron nodules dominate over iron staining, which reflects the effects of rapid oxidation (figure 4.53). There is little seasonal variability in either the percentage of iron nodules or iron staining. Conversely, the results for the air dried experiment group show that iron staining dominates over iron nodules reflecting the effects of slow oxidation (figure 4.54). Again, there is little seasonal variation for both nodules and staining. Finally, the control group has a higher proportion of staining to nodules, which is representative of the hydrological environment at Savernake (figure 4.55). The slow oxidation resulting from natural groundwater fluctuations has resulted in prevalent iron staining. There is slightly more seasonal variation for the control group, which reflects the seasonal fluctuation of the groundwater table at Savernake.

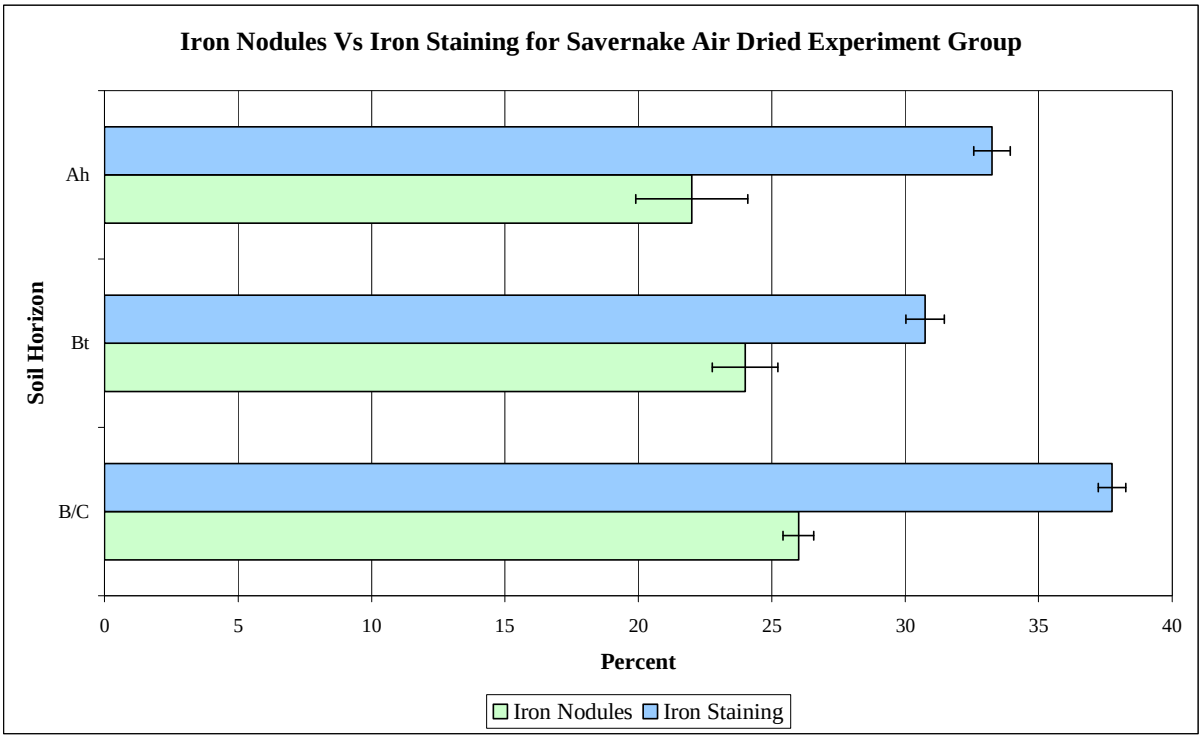


Figure 4.54. Mean percentage of iron nodules and iron staining, and the seasonal variation (error bars) for the air dried experiment group at Savernake.

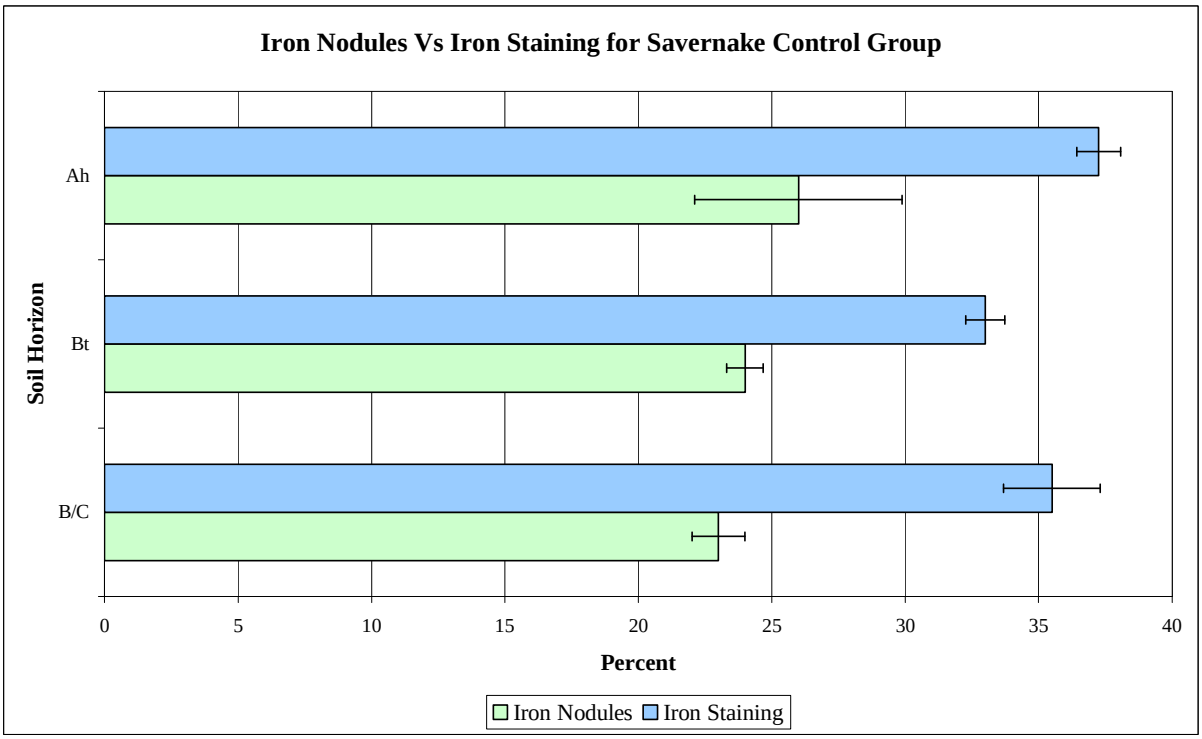


Figure 4.55. Mean percentage of iron nodules and iron staining, and the seasonal variation (error bars) for the control group at Savernake.

4.4.2.3 Organic Material

Table 4.17 presents the percentage frequencies and preservation state for the organic material identified through soil micromorphological analysis. In addition to the frequencies and the state of preservation of the organic material, the size range for celled material, and whether or not the organic material is associated with iron oxide, is also noted (appendix F).

Fine organic punctuations and amorphous organic material dominate the organic fraction of the soil at Savernake. There does not appear to be any main differences between experiment groups or seasons for these two types of organic material and there is a greater amount in the A horizon, which is not surprising. The celled material, on the other hand, reveals a different picture with higher quantities in the control group than in the oven and air dried experiment groups, and again with much of this concentrated in the A horizon. The preservation of the celled material varies mainly between yellow to red brown (with a few smatterings of fresh and black material), which would suggest that the organic material is in the early stages of decomposition. Charcoal is present in greater amounts in the <100µm size range than in the >100µm size range, which suggests a presence in the soil. There is a significant quantity of pollen present, which is not surprising given the acidic nature of the soil environment at Savernake. Plectenchymae (fungi), namely sclerotia, are present in the soil at Savernake with a slight increase in quantity in the control group. However, according to Bullock *et al.* (1985, 78), sclerotia are better preserved in soils that are acetone replaced than in soils that have been subjected to other methods, such as air drying.

Given the differences between the experiment groups for the celled organic material, the oxidation experiments appear to have affected the preservation of plant material at Savernake. However, the uniform patterns present for the organic punctuations and organic matter suggest that such conclusions should be drawn with care. I believe that with time the oxidation conditions would indeed have a much greater effect on the preservation of organic material at this site but unfortunately, given the time constraints for this project, such inferences cannot be empirically supported here.

Table 4.17. Percentage of organic material for Savernake identified through micromorphological analysis.

Sample Number		Soil Horizon	Amorphous		Charcoal		Celled			Plectenchyma (Fungi)	Pollen
			Punctuations	Matter	< 100um	> 100um	Lignified	Parenchymatic	Phlobaphene		
October 2003	1.1	Ah	■■■■■■■■	■■■■■■■	■■	■■	■■ 1-3	■■ 1-3	■■ 3	■ 3-5	■■
	1.2	Bt	■■■■■■	■■■■■	■■■	■■		■■ 2-3		■ 3-5	■
	1.3	B/C	■■■■■	■■■	■■						
	2.1	Ah	■■■■■■■	■■■■■■	■■	■	■ 1-3	■ 2-3	■ 3	■ 3	■■■
	2.2	Bt	■■■■■■	■■■■■	■■■	■	■ 1-3	■ 1-2		■ 3-5	■■
	2.3	B/C	■■■■■	■■■	■■	■	■ 2-3				■■
	3.1	Ah	■■■■■■■	■■■■■■	■■■	■	■■■ 2-3	■ 2-3	■ 3	■ 3-5	■■
	3.2	Bt	■■■■■■	■■■■■	■■■	■■	■ 2-3	■ 2	■ 3	■ 3	■■
	3.3	B/C	■■■■	■■■	■■	■	■ 2-3			■ 3-5	■■■
January 2004	1.1	Ah	■■■■■■■	■■■■■■	■■■	■	■ 1-3	■■ 1-3	■ 3	■ 3	■■
	1.2	Bt	■■■■■	■■■■	■■■	■	■ 4-5	■ 2-5		■ 3	■■
	1.3	B/C	■■■■	■■■	■■	■					■■
	2.1	Ah	■■■■■■■	■■■■■■	■■■	■	■ 2-3	■■ 2-3		■ 3	■■
	2.2	Bt	■■■■■	■■■■	■■■	■			■ 3	■ 3	■■■
	2.3	B/C	■■■■	■■	■■	■	■ 2-3	■ 2-5		■ 3-5	■■■
	3.1	Ah	■■■■■■■	■■■■■■	■■■	■	■■■■ 2-3	■■ 2-3	■■ 3	■■ 3-5	■■
	3.2	Bt	■■■■■■	■■■■■	■■■	■■	■ 2-3	■ 2-3		■ 3-5	■■
	3.3	B/C	■■■■■	■■■	■■■	■		■ 2-3		■ 3-5	■■
April 2004	1.1	Ah	■■■■■■■	■■■■■■	■■■	■	■■ 2-3	■ 2-3	■ 3		■■■
	1.2	Bt	■■■■■■	■■■■■	■■■	■■	■ 3-5	■ 2-5	■ 3	■ 3-5	■■■
	1.3	B/C	■■■■■	■■■	■■	■		■ 2-3		■ 3-5	■■■
	2.1	Ah	■■■■■■■	■■■■■■	■■■	■	■■ 2-3	■■ 2-3	■■ 3		■■
	2.2	Bt	■■■■■■	■■■■■	■■■	■	■■ 2-3	■ 2-3	■ 3	■ 3-5	■■■
	2.3	B/C	■■■■■	■■■	■■■	■■■				■ 5	■■■
	3.1	Ah	■■■■■■■	■■■■■■	■■■	■	■■■■ 2-3	■■■■ 2-3	■■■■ 3	■ 3-5	■■
	3.2	Bt	■■■■■■	■■■■■	■■■	■	■ 2-3	■■ 2-3		■ 3-5	■■■
	3.3	B/C	■■■■■	■■■■	■■	■	■ 2-3	■ 2-3		■ 3-5	■■■
July 2004	1.1	Ah	■■■■■■■	■■■■■■	■■■	■	■ 2-3	■■ 2-3	■ 3		■■■
	1.2	Bt	■■■■■	■■■■	■■■	■	■ 2	■ 2-3		■ 3-5	■■■
	1.3	B/C	■■■■■	■■■■	■■	■		■ 2-3		■ 3-5	■■■
	2.1	Ah	■■■■■■■	■■■■■	■■■	■■	■ 2-3	■ 2-3		■ 3-5	■■■
	2.2	Bt	■■■■■■	■■■■■	■■■	■				■ 3-5	■■■
	2.3	B/C	■■■■	■■■	■■	■				■ 3-5	■■■
	3.1	Ah	■■■■■■■	■■■■■■	■■■	■	■■■ 2-3	■■■ 2-3	■■■ 3	■ 3-5	■■■■
	3.2	Bt	■■■■■	■■■■	■■	■		■ 2-3			■■■■
	3.3	B/C	■■■■■	■■■	■■	■	■ 2	■ 2-3		■ 3-5	■■■

Key: ■ <2%, ■■ 2-5%, ■■■ 5-10%, ■■■■ 10-20%, ■■■■■ 20-30%, ■■■■■■ 30-40%, ■■■■■■■ 40-50%, ■■■■■■■■ 50-60%, ■■■■■■■■■ 60-70%

Key to preservation of organic material: 1 = fresh; 2 = yellow; 3 = red-brown; 4 = brown; 5 = black

4.4.3 CDB for an Argillic Pelosol

Although the soils at Savernake are more susceptible to seasonal variation than the other sites examined during the course of this research, this variability has a minimal impact on the overall results for the bulk and the soil micromorphological data. While it is important to note that argillic pelosols, such as Savernake, are influenced by the seasonal fluctuations of the groundwater table, the impermeable nature of these soils, and the reducing-oxidising cycles that occur in this environment, provide an ideal opportunity to study the effects of different rates of oxidation. As was noted earlier, the iron oxide deposition patterns for the control group are simulated in the air dried experiment group, confirming the effects of slow oxidation caused by natural fluctuations in the groundwater table.

The comparative database (CDB), as represented by the two graphs below (figures 4.56 and 4.57), was formed by combining the bulk and soil micromorphological data for the experiment groups at Savernake. These graphs highlight the variables that are most likely to provide the best representation of the oxidation environment within the soil, in a way that is functional and clear as a reference guide to gauging preservation.

The means for each bulk and selected micromorphological variable have been used to formulate the graphs in figures 4.56 and 4.57 in reference to their soil depth and soil horizon. For each figure, a sedimentological key is provided to represent the soil profile at the site, and the corresponding bulk and soil micromorphological results are mapped out in accordance with their context in the soil profile. Two variables from the soil micromorphological analyses have been used for these graphs: iron nodules and iron staining, as these variables prove the most informative for determining the oxidation and/or hydrological environment for an argillic pelosol such as Savernake.

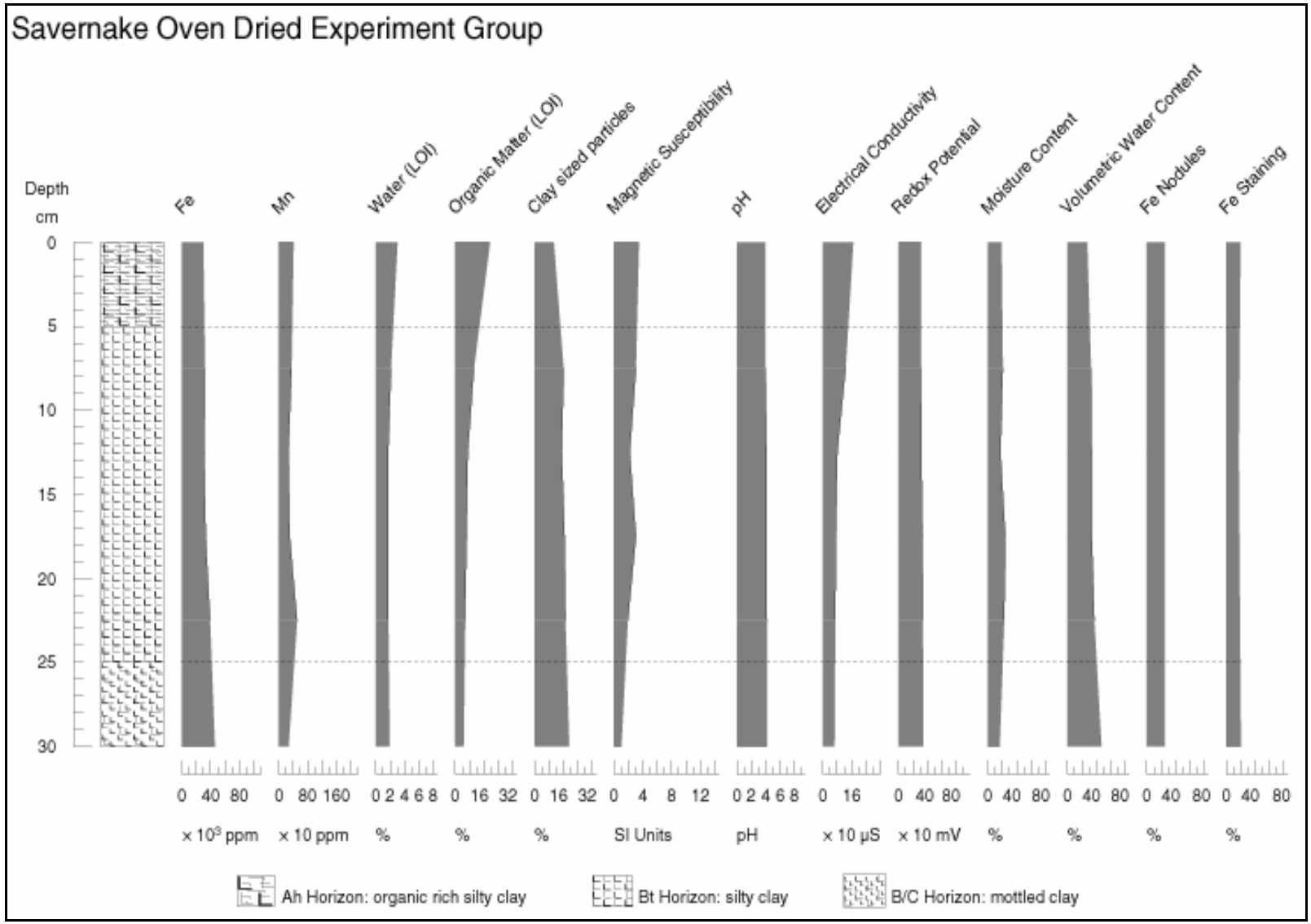


Figure 4.56. The comparative database (CDB) for the Savernake oven dried experiment group.

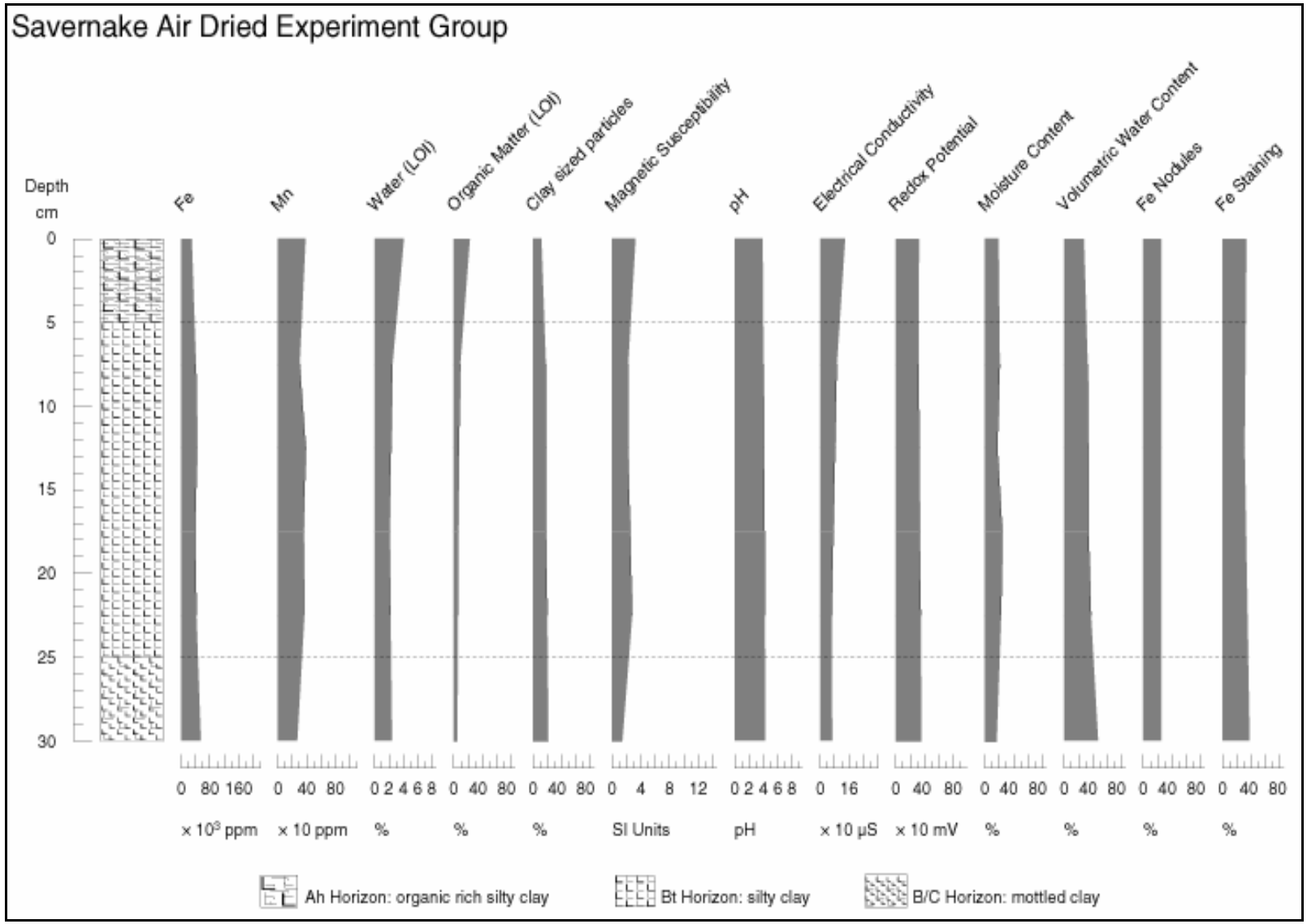


Figure 4.57. The comparative database (CDB) for the Savernake air dried experiment group.

The bulk analyses results for Savernake show no clear variation between experiment groups, however, the micromorphological data reveal distinct differences between the percentages of iron staining and iron nodules for both the oven dried and air dried experiment groups. The oven dried experiment group, representing **rapid** oxidation of the soil, has a higher proportion of iron **nodules** to iron staining, whereas the air dried experiment group, representing **slow** oxidation of the soil, has a higher proportion of iron **staining** to iron nodules. These results suggest that iron staining and iron nodules, as identified through soil micromorphology, are the most informative variables for identifying the oxidation processes within the soil environment. Further, the effects that different oxidising conditions have on the organic material present in the soil are indicated by the decomposition and disintegration of the organic material, identified in thin section, for the experiment groups and the control group. The control group has a higher proportion of celled organic material present in the soils than either of the experiment groups. Although there appears to be no distinct differences in organic preservation between the experiment groups, I would suggest that over time significant differences could be identified with a higher proportion of organic decomposition resulting from rapid oxidation than from slow oxidation (cf. Welch and Thomas 1998). This is supported through the results of the control group, as Savernake is currently subjected to slow oxidation through the natural seasonal fluctuations of the groundwater table.

4.5 SHERWOOD

Sherwood is an acidic brown podzolic soil under a Scots Pine forest environment on a steeply dissected valley slope. The results of the bulk and soil micromorphological analyses (see table 3.1 in section 3.2) follow for each experiment group.

4.5.1 Bulk Analyses Data

A suite of bulk analyses were conducted on the oven dried and air dried bulk samples (see table 3.1 in section 3.2). Moisture content and VWC were recorded prior to the oxidation experiments and rainfall data was collected from Forestry Services. The results for each analysis for the oven dried group are presented here, followed by the results for the air dried group.

4.5.1.1 The Normal Curve and Seasonal Variation

The data for each analysis were tested for normal distribution by using a one-sampled K-S test (Field 2005). If the result is $p>.05$, then the data are deemed normally distributed. The results of this test for all the bulk analyses (oven dried group followed by air dried group) are presented in tables 4.18 and 4.19.

Table 4.18. Results of the normal distribution test for the air dried group across all seasons. The value highlighted in bright blue indicates that this group is *not* normally distributed.

One-Sample Kolmogorov-Smirnov Test for Sherwood Oven Dried Experiment Group

		Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox (mV)	Bulk Density (%)	Volumetric Water Content (%)
N		24	24	24	24	24	24	24	24	24	24	24
Normal Parameters[a,b]	Mean	29562.50	210.38	3.62	12.20	2.26	8.70	4.18	63.63	320.76	23.91	23.26
	Std. Deviation	3664.26	55.27	2.35	2.72	.47	4.26	.22	28.70	13.07	9.02	13.59
Most Extreme Differences	Absolute	.14	.15	.12	.15	.14	.28	.11	.11	.13	.13	.16
	Positive	.08	.12	.11	.12	.14	.28	.11	.11	.09	.11	.16
	Negative	-.14	-.15	-.12	-.15	-.06	-.24	-.10	-.09	-.13	-.13	-.11
Kolmogorov-Smirnov Z		.67	.75	.60	.72	.69	1.36	.55	.52	.66	.64	.77
Asymp. Sig. (2-tailed)		.76	.63	.86	.67	.73	.05	.93	.95	.78	.81	.59

a. Test distribution is Normal.

b. Calculated from data.

Table 4.19. Results of the normal distribution test for the air dried group across all seasons. The value highlighted in bright blue indicates that this group is *not* normally distributed.

One-Sample Kolmogorov-Smirnov Test for Sherwood Air Dried Experiment Group

		Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox (mV)	Bulk Density (%)	Volumetric Water Content (%)
N		24	24	24	24	24	24	24	24	24	24	24
Normal Parameters[a,b]	Mean	30600.00	212.04	3.39	13.15	2.89	8.94	4.24	64.40	318.40	23.91	23.26
	Std. Deviation	4565.18	50.00	2.27	2.76	.71	4.95	.24	35.21	16.95	9.02	13.59
Most Extreme Differences	Absolute	.14	.17	.15	.13	.26	.33	.11	.19	.12	.13	.16
	Positive	.14	.12	.15	.13	.26	.33	.07	.19	.07	.11	.16
	Negative	-.12	-.17	-.12	-.06	-.20	-.25	-.11	-.16	-.12	-.13	-.11
Kolmogorov-Smirnov Z		.67	.83	.76	.65	1.25	1.59	.53	.95	.60	.64	.77
Asymp. Sig. (2-tailed)		.76	.50	.62	.79	.09	.01	.94	.33	.86	.81	.59

a. Test distribution is Normal.

b. Calculated from data.

Data from the oven dried experiment group for Sherwood are normally distributed except for the %OM (LOI) data. This variable is on the cusp at $p = .05$ but as p is not greater than .05 it is treated as being significantly different from a normal distribution. The data from the air dried experiment group for Sherwood are normally distributed with the exception of %OM (LOI). In order to assess seasonal variability at Sherwood, the means and standard errors were calculated for each bulk analysis and experiment group. The results are presented using bar graphs with error bars, as in figures 4.58 to 4.68 below.

Figures 4.58 to 4.66 represent seasonal variation for each of the bulk analyses for both the oven dried experiment group and the air dried experiment group. Generally, the bulk analyses results for Sherwood show little variation between experiment groups but for some variables, seasonal variation is apparent. Fe (figure 4.58), redox (figure 4.66), pH (figure 4.64), and %Clay (figure 4.62) show little to no seasonal variation and although %Clay is more variable than expected, this variability is not significant. As discussed above, these results are expected as the oxidation experiments are not going to directly influence these variables. Similarly, %OM has little seasonal variation with the exception of the 0-5cm samples for both experiment groups (figure 4.61). As the upper horizons of the Sherwood soil profile are organic-rich (O and H horizons), some variation is expected here and the seasonal variation could have been influenced by sampling, or by the variation in OM decomposition. There is also some seasonal variation for Mn (figure 4.59), especially in the upper, organic-rich horizons, which may also reflect the variation in OM decomposition with the release of plant nutrients, including Mn. This result is also reflected in the seasonal variation evident for the MS results (figure 4.63), with greater seasonal variation in the upper, organic-rich horizons, which represent the plant minerals released during decomposition that are magnetically susceptible.

Finally, there is significant variation for both %Water and EC within the 0-5cm samples, which suggests that water is being held in these organic-rich horizons even after oxidation. However, this seasonal variation is more evident in the air dried experiment group than in the oven dried experiment group, which suggests that the air dried group were more susceptible to variation in atmospheric moisture during the drying out process than the oven dried group.

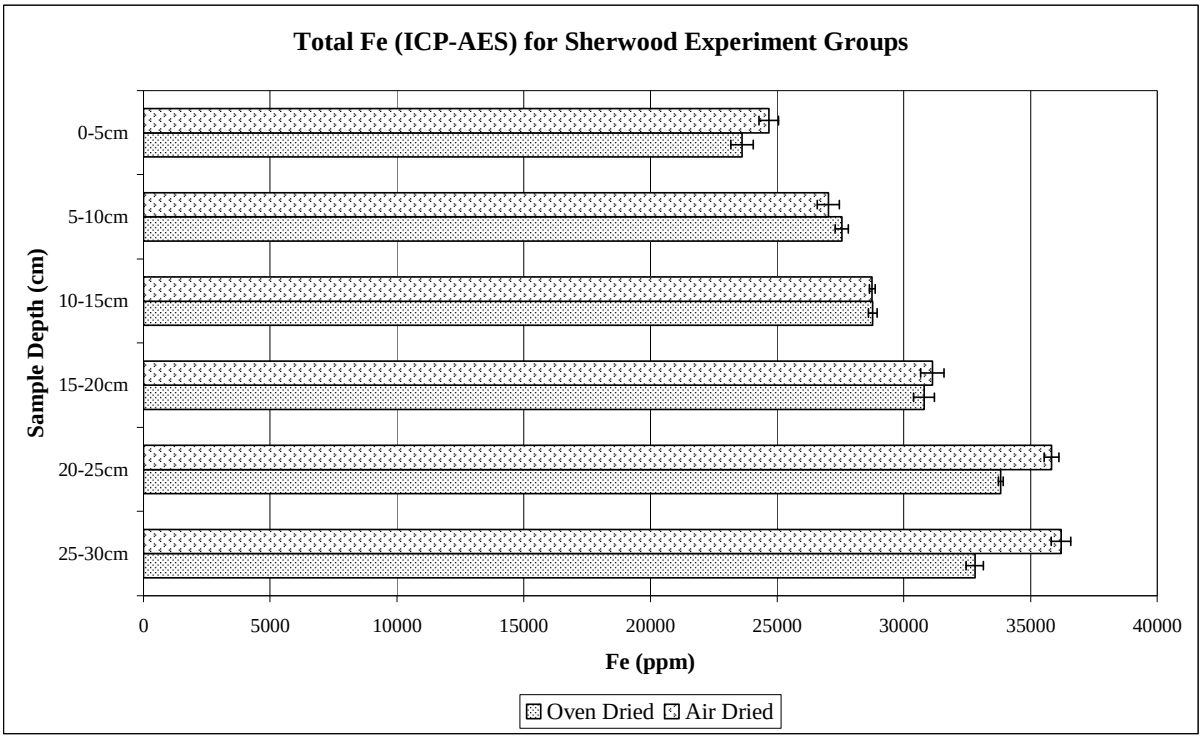


Figure 4.58. Mean and standard error for total Fe (ICP-AES) to determine seasonal variation for both the oven dried and air dried experiment groups.

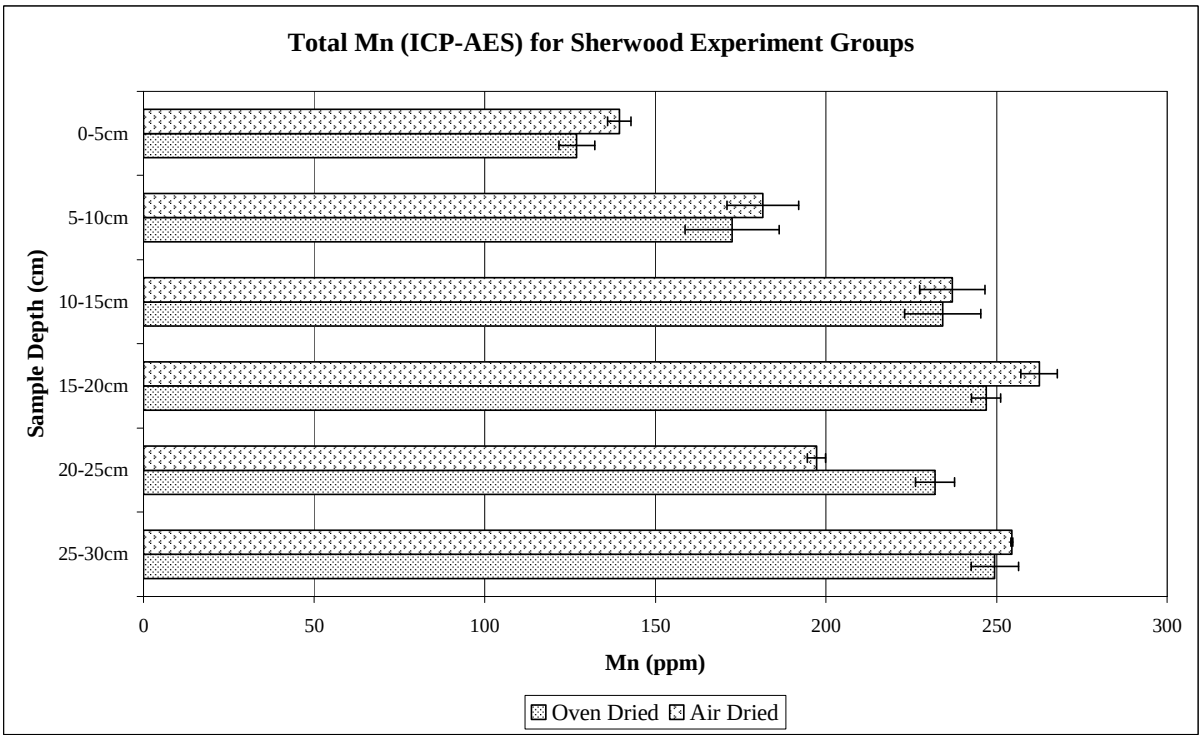


Figure 4.59. Mean and standard error for total Mn (ICP-AES) to determine seasonal variation for both the oven dried and air dried experiment groups.

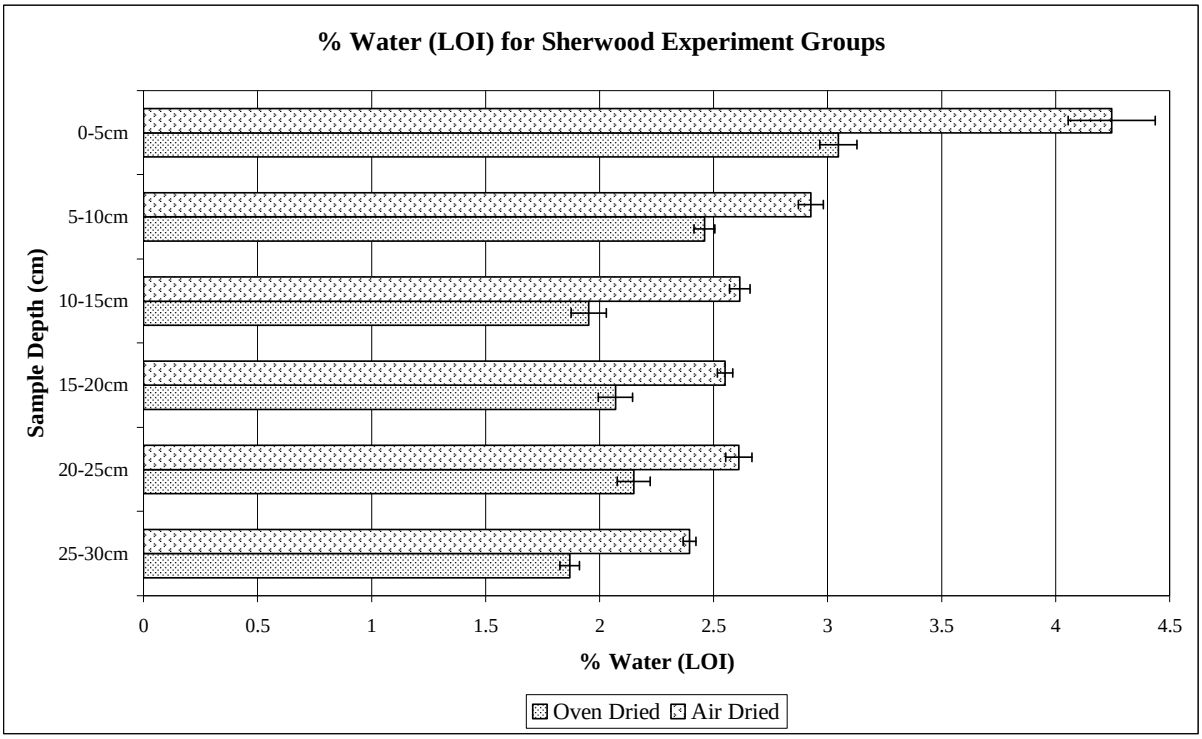


Figure 4.60. Mean and standard error for %Water (LOI) to determine seasonal variation for both the oven dried and air dried experiment groups.

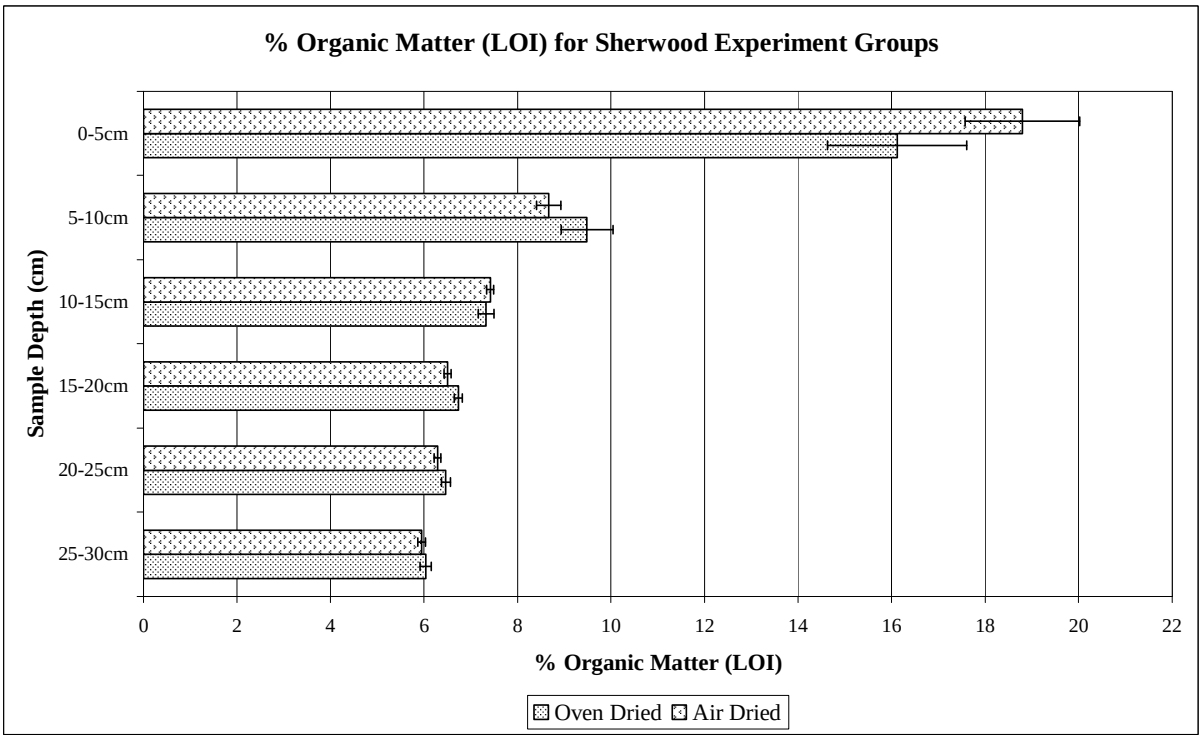


Figure 4.61. Mean and standard error for %Organic Matter (LOI) to determine seasonal variation for both the oven dried and air dried experiment groups.

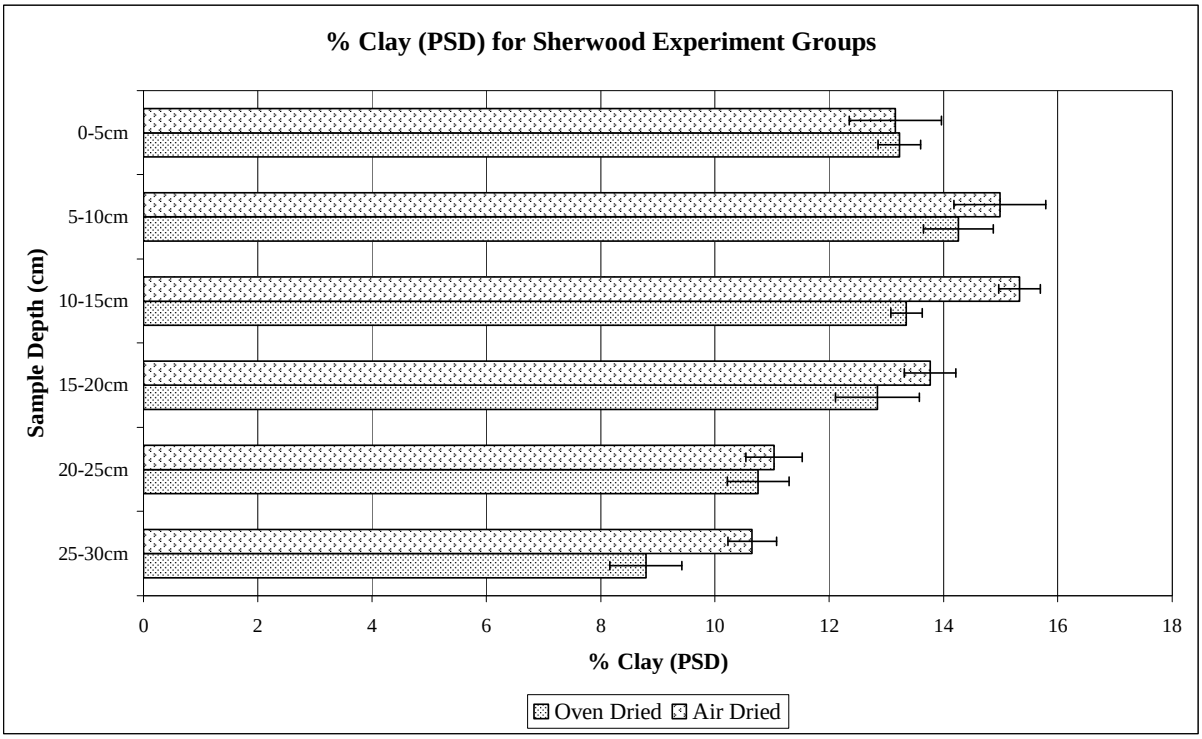


Figure 4.62. Mean and standard error for %Clay (PSD) to determine seasonal variation for both the oven dried and air dried experiment groups.

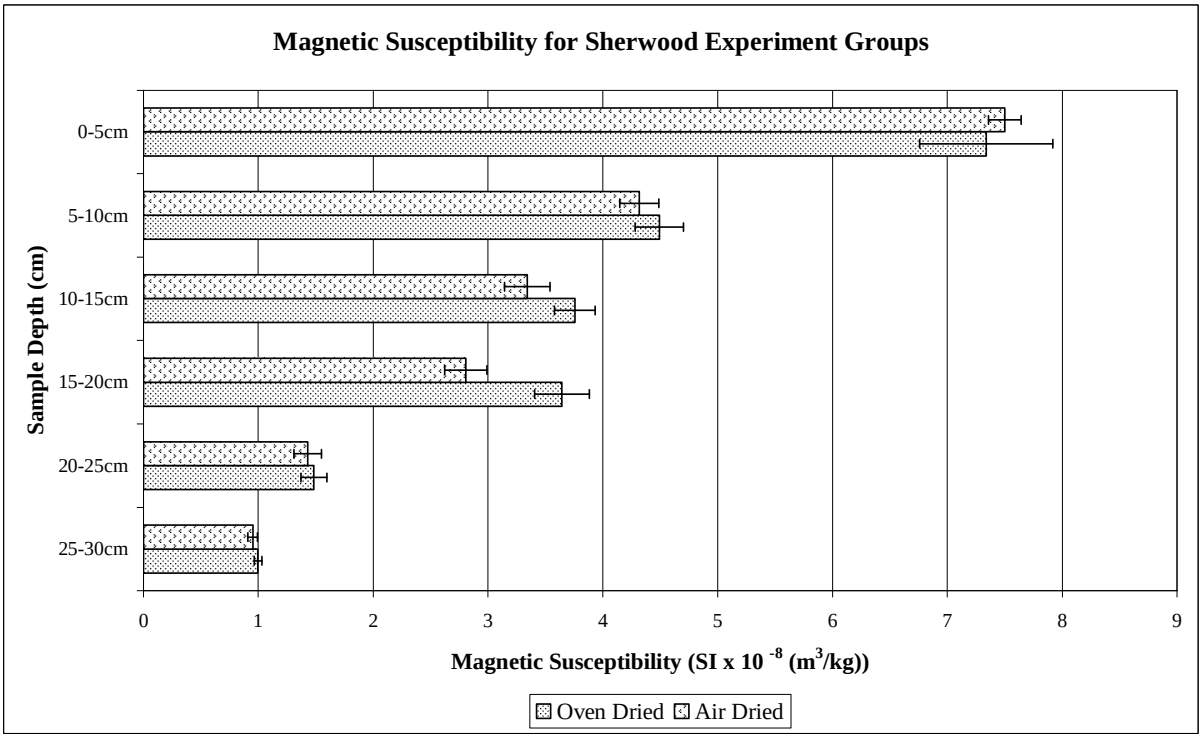


Figure 4.63. Mean and standard error for magnetic susceptibility to determine seasonal variation for both the oven dried and air dried experiment groups.

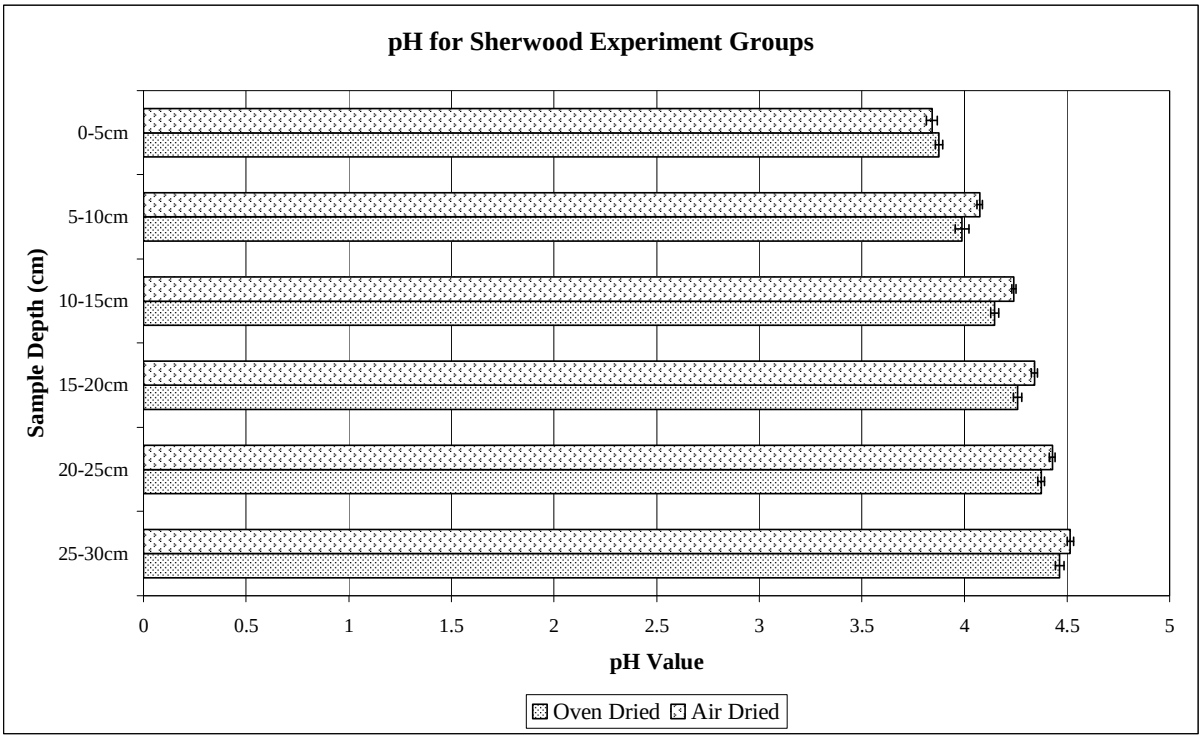


Figure 4.64. Mean and standard error for pH to determine seasonal variation for both the oven dried and air dried experiment groups.

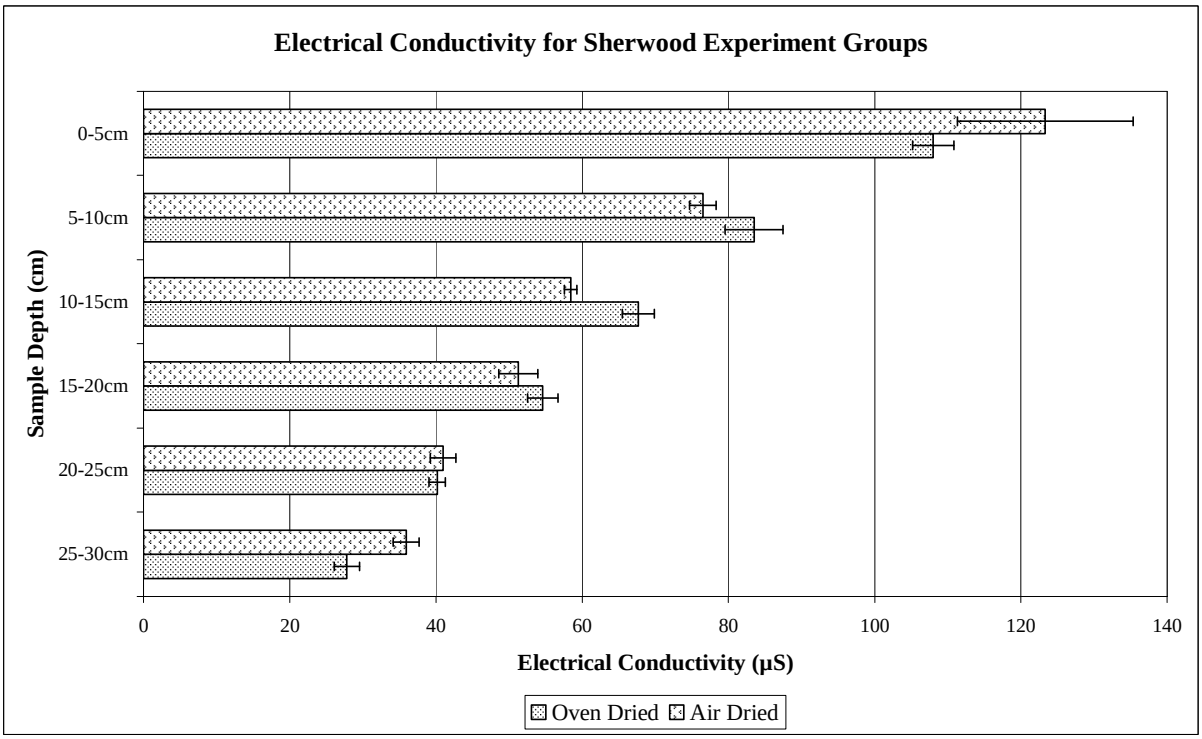


Figure 4.65. Mean and standard error for electrical conductivity to determine seasonal variation for both the oven dried and air dried experiment groups.

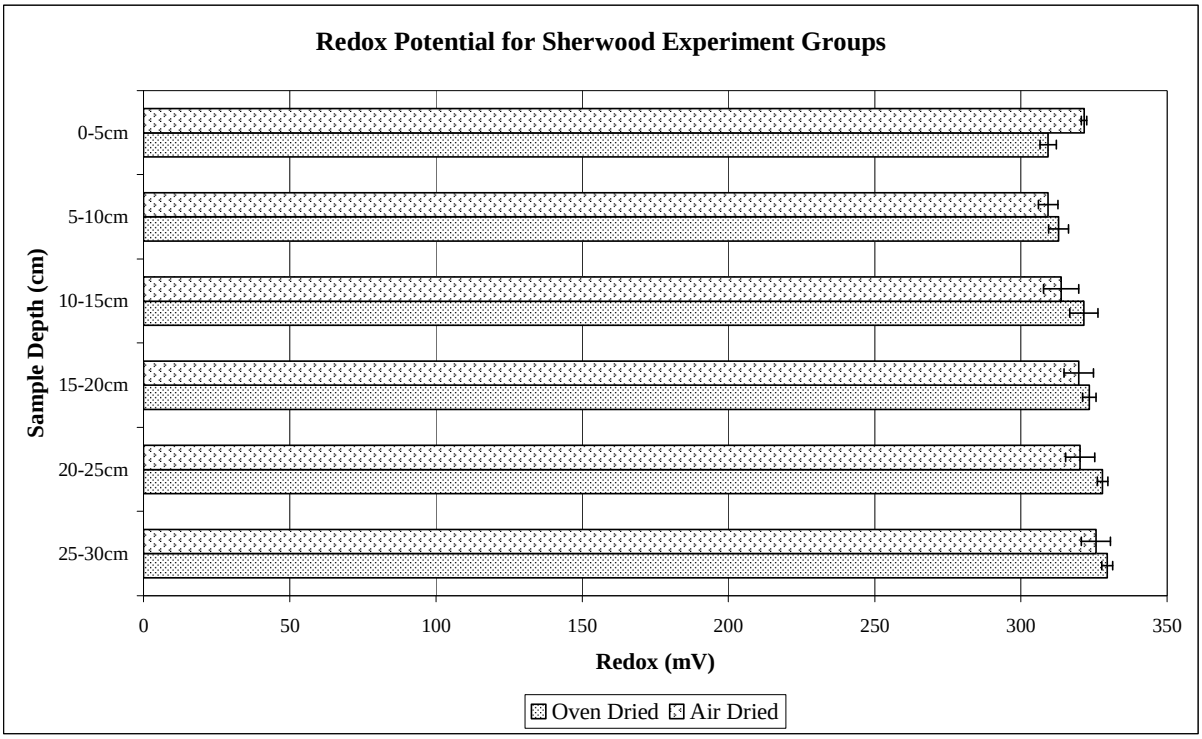


Figure 4.66. Mean and standard error for redox potential to determine seasonal variation for both the oven dried and air dried experiment groups.

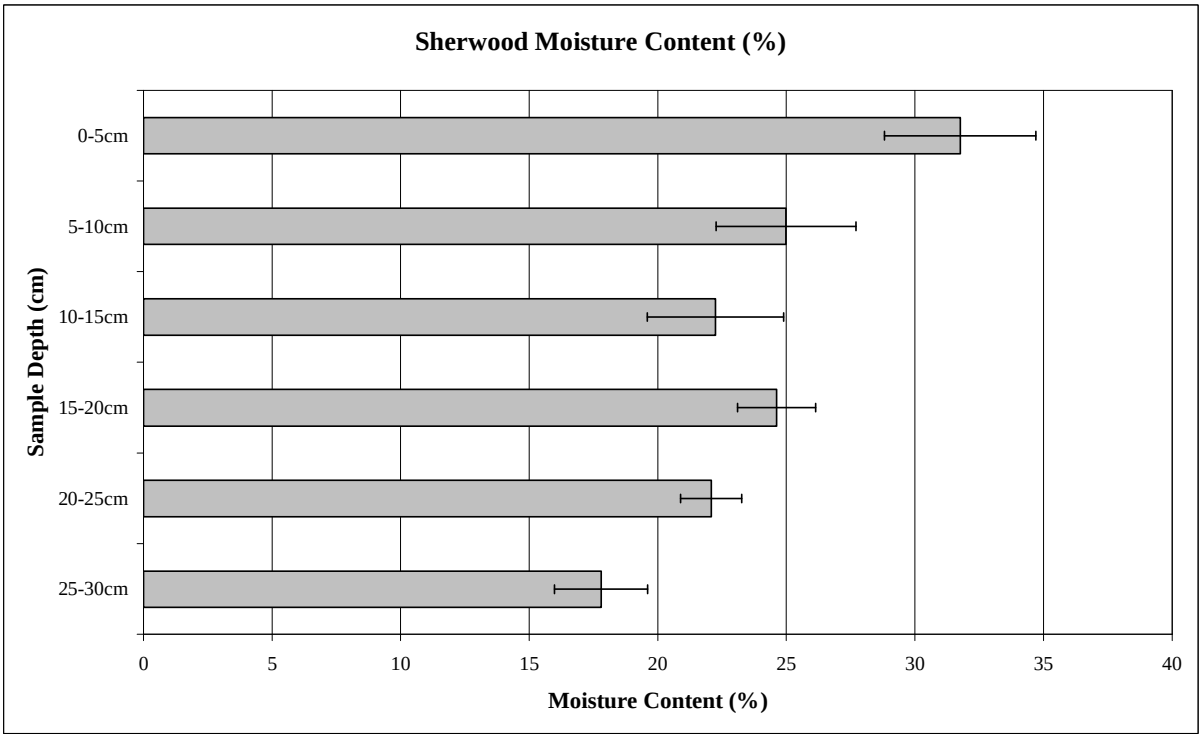


Figure 4.67. Mean and standard error to determine seasonal variation for the moisture content, taken prior to the oxidation experiments.

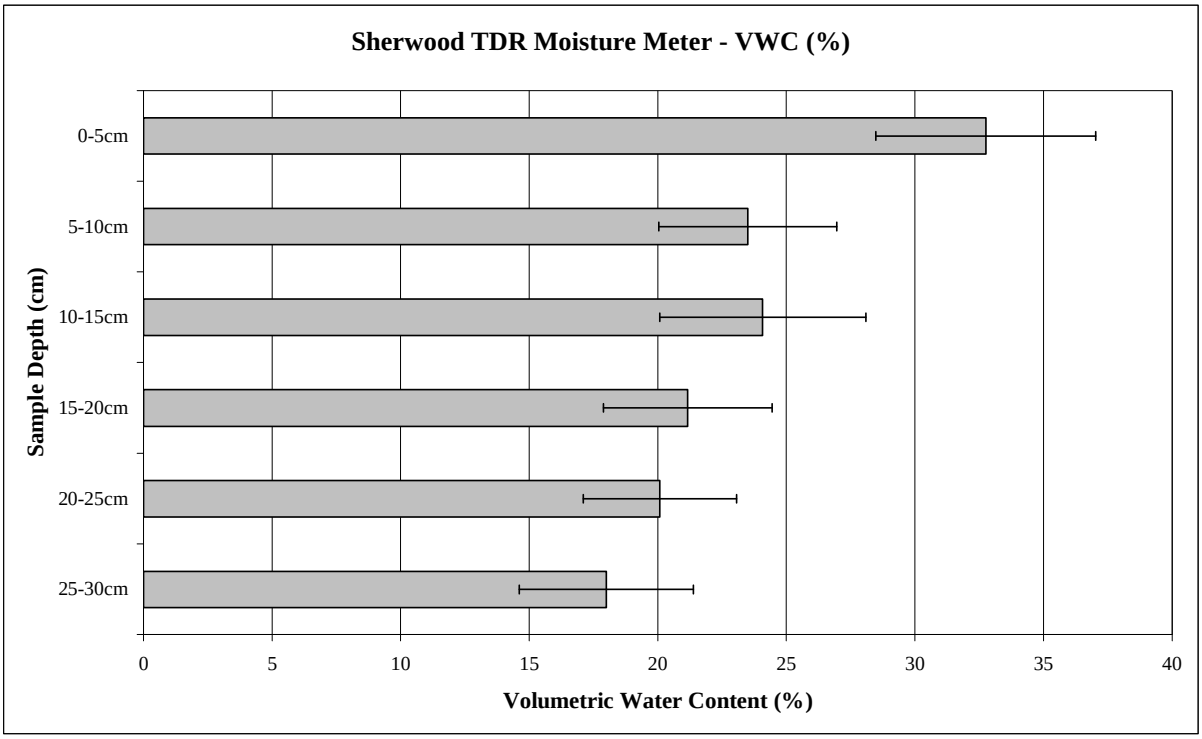


Figure 4.68. Mean and standard error to determine seasonal variation in soil moisture for the in-field measurements taken prior to sampling.

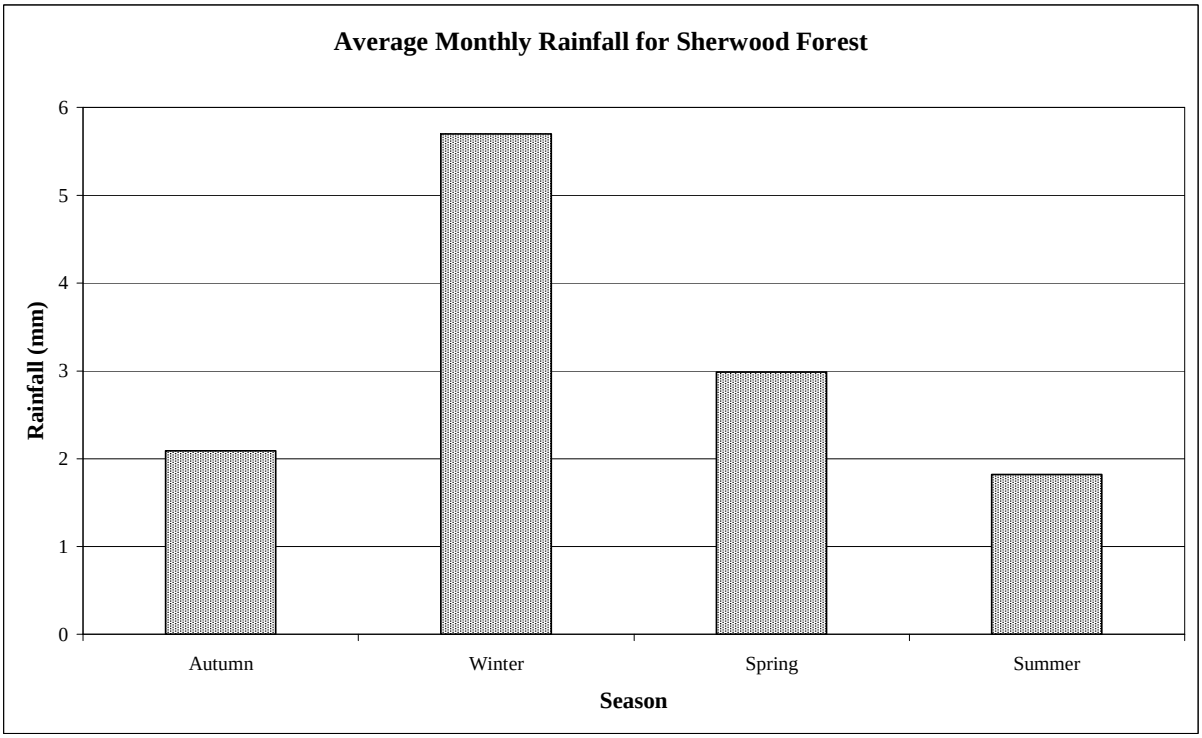


Figure 4.69. Total rainfall for Sherwood from autumn 2003 to summer 2004 (October 2003, January, April and July, 2004). This data was supplied by Forestry Services.

The results from the moisture content (figure 4.67), which is the percentage of moisture in the soil prior to the oxidation experiments, and the VWC from the in-field TDR moisture meter readings (figure 4.68) show more variation between seasons than the other bulk analyses data. This is expected as variation in rainfall will have a direct influence on the moisture readings for the soil. The rainfall records for the collection seasons show great variability, with a particularly wet period over the winter season and drier episodes in the autumn and summer (figure 4.69). As Sherwood is a brown podzolic soil, eluviation and illuviation processes are dominant with the movement of fine material (organics and clay) down profile in colloidal suspension with rainwater (which is also evident from the micromorphological analyses below). Therefore, the variation and quantity of rainfall at Sherwood have direct influences on the soil formation processes.

4.5.1.2 Correlation Coefficients and Relationships

As the data for both the oven dried experiment group and air dried experiment group for Sherwood are not normally distributed (tables 4.18 and 4.19), Spearman's rho correlation coefficient was used to highlight relationships between the different analytical variables (Field 2005). Although relationships between variables were expected, the direction of the relationships was not predicted; therefore, a two-tailed significance test was used (*ibid*). These results are presented in tables 4.20 and 4.21 below.

Table 4.20. Spearman's rho correlation was used for the Sherwood oven dried experiment group as the data are not normally distributed. Significant correlations are highlighted.

Correlations for Sherwood Oven Dried Experiment Group

			Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox (mV)	Bulk Density (%)	Volumetric Water Content (%)
Spearman's rho	Fe (ppm)	Correlation Coefficient	1.000	.570**	-.776**	-.419*	-.724**	-.769**	.801**	-.840**	.568**	-.295	-.318
		Sig. (2-tailed)	.	.004	.000	.042	.000	.000	.000	.000	.004	.162	.129
		N	24	24	24	24	24	24	24	24	24	24	24
	Mn (ppm)	Correlation Coefficient	.570**	1.000	-.473*	-.399	-.755**	-.624**	.598**	-.638**	.515*	-.187	-.191
		Sig. (2-tailed)	.004	.	.020	.053	.000	.001	.002	.001	.010	.383	.372
		N	24	24	24	24	24	24	24	24	24	24	24
	Magnetic Susceptibility (SI Units)	Correlation Coefficient	-.776**	-.473*	1.000	.668**	.583**	.902**	-.935**	.922**	-.715**	.479*	.095
		Sig. (2-tailed)	.000	.020	.	.000	.003	.000	.000	.000	.000	.018	.658
		N	24	24	24	24	24	24	24	24	24	24	24
	% Clay (PSD)	Correlation Coefficient	-.419*	-.399	.668**	1.000	.204	.570**	-.621**	.668**	-.516**	.316	.174
		Sig. (2-tailed)	.042	.053	.000	.	.338	.004	.001	.000	.010	.133	.415
		N	24	24	24	24	24	24	24	24	24	24	24
	% Water (LOI)	Correlation Coefficient	-.724**	-.755**	.583**	.204	1.000	.634**	-.612**	.634**	-.470*	.180	.263
		Sig. (2-tailed)	.000	.000	.003	.338	.	.001	.001	.001	.020	.400	.215
		N	24	24	24	24	24	24	24	24	24	24	24
	% Organic Matter (LOI)	Correlation Coefficient	-.769**	-.624**	.902**	.570**	.634**	1.000	-.973**	.944**	-.652**	.465*	.055
		Sig. (2-tailed)	.000	.001	.000	.004	.001	.	.000	.000	.001	.022	.798
		N	24	24	24	24	24	24	24	24	24	24	24
	pH Value	Correlation Coefficient	.801**	.598**	-.935**	-.621**	-.612**	-.973**	1.000	-.967**	.697**	-.483*	-.068
		Sig. (2-tailed)	.000	.002	.000	.001	.001	.000	.	.000	.000	.017	.751
		N	24	24	24	24	24	24	24	24	24	24	24
	Electrical Conductivity (µS)	Correlation Coefficient	-.840**	-.638**	.922**	.668**	.634**	.944**	-.967**	1.000	-.689**	.408*	.156
		Sig. (2-tailed)	.000	.001	.000	.000	.001	.000	.000	.	.000	.048	.468
		N	24	24	24	24	24	24	24	24	24	24	24
	Redox (mV)	Correlation Coefficient	.568**	.515*	-.715**	-.516**	-.470*	-.652**	.697**	-.689**	1.000	-.005	.344
		Sig. (2-tailed)	.004	.010	.000	.010	.020	.001	.000	.000	.	.981	.100
		N	24	24	24	24	24	24	24	24	24	24	24
	Bulk Density (%)	Correlation Coefficient	-.295	-.187	.479*	.316	.180	.465*	-.483*	.408*	-.005	1.000	.504*
		Sig. (2-tailed)	.162	.383	.018	.133	.400	.022	.017	.048	.981	.	.012
		N	24	24	24	24	24	24	24	24	24	24	24
	Volumetric Water Content (%)	Correlation Coefficient	-.318	-.191	.095	.174	.263	.055	-.068	.156	.344	.504*	1.000
		Sig. (2-tailed)	.129	.372	.658	.415	.215	.798	.751	.468	.100	.012	.
		N	24	24	24	24	24	24	24	24	24	24	24

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

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

Correlations with significance levels of $p<.05$ and $p<.01$ are marked by asterisks in each of the correlation tables. I will first discuss the correlations for the oven dried experiment group, followed by the air dried experiment group for Sherwood.

In the oven dried experiment group (table 4.20) there are several correlations with Fe including Mn ($r_s = .570$, $p<.01$), MS ($r_s = -.776$, $p<.0001$), %Clay ($r_s = -.419$, $p<.05$), %Water ($r_s = -.724$, $p<.0001$), %OM ($r_s = -.769$, $p<.0001$), pH ($r_s = .801$, $p<.0001$), EC ($r_s = -.840$, $p<.0001$), and redox ($r_s = .568$, $p<.01$). The positive correlation with Mn is expected as these minerals behave in similar ways, as is evident from the similar correlations Mn has with the same variables: MS ($r_s = -.473$, $p<.05$), %Water ($r_s = -.755$, $p<.0001$), %OM ($r_s = -.624$, $p<.001$), pH ($r_s = .598$, $p<.01$), EC ($r_s = -.638$, $p<.001$), and redox ($r_s = .515$, $p<.05$). The negative correlations that Fe and Mn have with MS indicate that MS readings are not necessarily picking up on these minerals, but may in fact be reading other minerals with magnetic properties, such as those that are released during organic decomposition (appendix G, table G-4). This is further confirmed by the positive correlation of MS with %OM ($r_s = .902$, $p<.0001$). In addition, the negative correlation between redox and MS ($r_s = -.715$, $p<.0001$) reflects the relationship of Fe and Mn with MS, as both these minerals are directly affected by redox processes. The negative correlations Fe and Mn have with %Water and their positive correlations with redox, suggest that the deposition of these minerals relates to the oxidising conditions within the soil. That is, there are low levels of moisture and high levels of oxidation, which is conducive to the deposition of Fe and Mn in their oxidised forms, identifiable through soil micromorphology. Further, the negative correlations that Fe and Mn have with EC reflect their relationship with %Water, and along with the low EC readings (figure 4.65), this suggests that the soluble salts have been leached from the soil, which is expected in podzolic conditions.

The negative correlations that Fe and Mn have with %OM suggest that the organic component of the soil is not the main source for these minerals. The negative correlation between redox and %OM ($r_s = -.652$, $p<.001$) is expected as the soil at Sherwood is rich in oxygen, which is a contributing factor to organic decomposition; therefore, the more oxidising the soil environment, the less OM present in the soil. Further, the negative relationship OM has with Fe and Mn may reflect the relationship of these minerals with %Water and EC, as OM has a great water holding capacity, as is confirmed with the positive correlation between %Water and %OM ($r_s = .634$, $p<.001$). Relative to the pH range at Sherwood (3.7-4.5), the positive correlations between this variable and Mn and Fe are expected as acidic conditions are

conducive to high quantities of Fe and Mn. This is further supported by the relationship between redox and pH (r_s = .697, p<.0001). Finally the correlation between %Clay and Fe reflects the distribution of these variables down the soil profile, and is representative of the leaching processes involved in the formation of podzolic soils. This is also reflected in the relationship between %Clay and redox (r_s = -.516, p<.05). Given the negative correlation between Fe and %Clay, suggesting that the clay is not rich in Fe, the positive correlation between MS and %Clay (r_s = .668, p<.0001) lends support to the non-magnetic nature of the Fe present in the soils at Sherwood. In addition, the MS readings are indicative of other magnetic plant nutrients that have been eluviated from the upper, organic horizons and illuviated down through the rest of the soil profile.

The relationship between MS and pH (r_s = -.935, p<.0001) reflects the conditions at Sherwood, i.e. Sherwood is an acidic site and the MS readings are within a moderate range (figure 4.63). The positive correlations between MS and %Water (r_s = .538, p<.01) and MS and EC (r_s = .902, p<.0001) are unclear, but the relationship of MS with each of these variables reflects the correlation between %Water and EC (r_s = .634, p<.001). Further, the correlation between EC and %OM (r_s = .944, p<.0001) is likely to be the result of water being held in the organic component of the soil, and as discussed above, MS has a positive correlation with %OM. Therefore, the relationship of MS with EC and %Water could be associated with the organic component of the soil. The positive correlation between MS and moisture content (r_s = .479, p<.05) reflects the relationship between MS and %Water (r_s = .583, p<.01), and in addition to the positive correlation between moisture content and %OM (r_s = .465, p<.05), suggests a similar scenario to MS and %Water.

The relationship between %Clay and pH (r_s = -.621, p<.001) reflects the environment at Sherwood: the soil is rich in clay and is acidic. Similarly, the positive correlation between %OM and %Clay (r_s = .570, p<.01) reflects the high quantities of organic material (namely in the upper horizons) and the clay-rich soils. Further, the positive correlation between EC and %Clay (r_s = .668, p<.0001) suggests that clay-rich soils have an effect on EC (Carroll and Oliver 2005). Further, the impermeable nature of clay-rich soils has an impact on the soil moisture content. In this light, the relationship between pH and %Water (r_s = -.612, p<.001) is expected as the site is acidic and, due to its impermeable nature, retains water even after the oxidation experiment (albeit in low quantities). The water holding capacity of the soil is further supported by the negative correlation between pH and moisture content (r_s = -.483,

Table 4.21. Spearman's rho correlation was used for the Sherwood air dried experiment group as the data are not normally distributed. Significant correlations are highlighted.

Correlations for Sherwood Air Dried Experiment Group

			Fe (ppm)	Mn (ppm)	Magnetic Susceptibility (SI Units)	% Clay (PSD)	% Water (LOI)	% Organic Matter (LOI)	pH Value	Electrical Conductivity (µS)	Redox (mV)	Bulk Density (%)	Volumetric Water Content (%)
Spearman's rho	Fe (ppm)	Correlation Coefficient	1.000	.479*	-.924**	-.478*	-.803**	-.909**	.919**	-.870**	.165	-.399	-.220
		Sig. (2-tailed)	.	.018	.000	.018	.000	.000	.000	.000	.442	.053	.302
		N	24	24	24	24	24	24	24	24	24	24	24
	Mn (ppm)	Correlation Coefficient	.479*	1.000	-.517**	-.055	-.655**	-.558**	.524**	-.512*	.306	-.381	-.121
		Sig. (2-tailed)	.018	.	.010	.798	.001	.005	.009	.011	.145	.067	.573
		N	24	24	24	24	24	24	24	24	24	24	24
	Magnetic Susceptibility (SI Units)	Correlation Coefficient	-.924**	-.517**	1.000	.511*	.787**	.919**	-.967**	.925**	-.141	.528**	.212
		Sig. (2-tailed)	.000	.010	.	.011	.000	.000	.000	.000	.511	.008	.319
		N	24	24	24	24	24	24	24	24	24	24	24
	% Clay (PSD)	Correlation Coefficient	-.478*	-.055	.511*	1.000	.210	.361	-.491*	.488*	-.105	.534**	.152
		Sig. (2-tailed)	.018	.798	.011	.	.324	.083	.015	.016	.626	.007	.478
		N	24	24	24	24	24	24	24	24	24	24	24
	% Water (LOI)	Correlation Coefficient	-.803**	-.655**	.787**	.210	1.000	.872**	-.835**	.753**	-.253	.283	.097
		Sig. (2-tailed)	.000	.001	.000	.324	.	.000	.000	.000	.233	.179	.651
		N	24	24	24	24	24	24	24	24	24	24	24
	% Organic Matter (LOI)	Correlation Coefficient	-.909**	-.558**	.919**	.361	.872**	1.000	-.943**	.839**	-.030	.363	.221
		Sig. (2-tailed)	.000	.005	.000	.083	.000	.	.000	.000	.888	.081	.300
		N	24	24	24	24	24	24	24	24	24	24	24
	pH Value	Correlation Coefficient	.919**	.524**	-.967**	-.491*	-.835**	-.943**	1.000	-.961**	.104	-.509*	-.280
		Sig. (2-tailed)	.000	.009	.000	.015	.000	.000	.	.000	.629	.011	.186
		N	24	24	24	24	24	24	24	24	24	24	24
	Electrical Conductivity (µS)	Correlation Coefficient	-.870**	-.512*	.925**	.488*	.753**	.839**	-.961**	1.000	-.167	.548**	.345
		Sig. (2-tailed)	.000	.011	.000	.016	.000	.000	.000	.	.435	.006	.099
		N	24	24	24	24	24	24	24	24	24	24	24
	Redox (mV)	Correlation Coefficient	.165	.306	-.141	-.105	-.253	-.030	.104	-.167	1.000	-.199	.159
		Sig. (2-tailed)	.442	.145	.511	.626	.233	.888	.629	.435	.	.352	.458
		N	24	24	24	24	24	24	24	24	24	24	24
	Bulk Density (%)	Correlation Coefficient	-.399	-.381	.528**	.534**	.283	.363	-.509*	.548**	-.199	1.000	.504*
		Sig. (2-tailed)	.053	.067	.008	.007	.179	.081	.011	.006	.352	.	.012
		N	24	24	24	24	24	24	24	24	24	24	24
	Volumetric Water Content (%)	Correlation Coefficient	-.220	-.121	.212	.152	.097	.221	-.280	.345	.159	.504*	1.000
		Sig. (2-tailed)	.302	.573	.319	.478	.651	.300	.186	.099	.458	.012	.
		N	24	24	24	24	24	24	24	24	24	24	24

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

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

p<.05). The correlations between redox and %Water (r_s = -.470, p<.05) and redox and EC (r_s = -.689, p<.0001) reflect the idea that in oxidising conditions, the availability of moisture and soluble salts is limited.

The negative correlation between pH and %OM (r_s = -.973, p<.0001) is expected as the soil is acidic and high quantities of OM increases the acidity of the soil. The relationship between pH and EC (r_s = -.967, p<.0001) reflects the relationship between pH and %Water, as soluble salts that are present in the soils will be held in the soil moisture content. Further, the correlation between EC and moisture content (r_s = .408, p<.05) confirms that the site is acidic and has a great water holding capacity with available soluble salts present; albeit in low quantities (figure 4.65).

Along with the positive correlation between Fe and Mn (r_s = .479, p<.05), these variables have similar correlations with a number of other variables within the air dried experiment group (table 4.21). For Fe, these include MS (r_s = -.924, p<.0001), %Clay (r_s = -.478, p<.05), EC (r_s = -.870, p<.0001), %Water (r_s = -.803, p<.0001), %OM (r_s = -.909, p<.0001), and pH (r_s = .919, p<.0001). The correlations for Mn include MS (r_s = -.517, p<.01), %OM (r_s = -.558, p<.01), pH (r_s = .524, p<.01), %Water (r_s = -.655, p<.001) and EC (r_s = -.512, p<.05). The positive correlation between Fe and Mn is expected, and the corresponding relationships of Fe and Mn with similar variables confirm the similar behaviour of these minerals in the soil environment.

The negative correlations of Fe and Mn with MS indicate that these minerals are not the main source of MS. It is more likely that the MS readings are linked with the organic decomposition within the soils at Sherwood, the subsequent leaching of these minerals, and their deposition further down the soil profile. This illuviation of fine material down the soil profile is evident in the soil micromorphological analyses below, and is further confirmed by the positive correlation between MS and %OM (r_s = .919, p<.0001). Further, the negative correlations of Fe and Mn with %OM suggest that the OM is not the main source for these minerals. Therefore, the MS at Sherwood is more likely to lie in the deposition of other magnetic minerals, such as copper or cobalt, from the decomposition of OM (appendix G, table G-4). The negative correlations of Fe and Mn with %Water and EC suggest low moisture content in the soil at Sherwood, and a general leaching of available soluble salts from the soil profile. This is consistent with the process of podzolisation. Relative to the pH range at Sherwood, the positive correlation of Fe and Mn with pH reflects the acidic nature of

the soils and its suitable environment for high quantities of Fe and Mn. Finally, the negative correlation between Fe and %Clay reflects the relative distribution of each of these variables down the soil profile, and is representative of the eluviation processes associated with podzolisation. In addition, the positive correlation between MS and %Clay (r_s = .511, p<.05) lends support to the non-magnetic nature of Fe present in the soils at Sherwood.

The correlations between MS and %Water (r_s = .787, p<.0001), MS and EC (r_s = .925, p<.0001), and MS and moisture content (r_s = .528, p<.01) are unclear but it is likely that these relationships are reflecting the relationship between %Water and EC (r_s = .753, p<.0001), EC and moisture content (r_s = .548, p<.01), and EC and %OM (r_s = .839, p<.0001). That is, EC is affected by soil moisture and OM, and as %OM is correlated with %Water (r_s = .872, p<.0001) and EC (r_s = .839, p<.0001), and MS and %OM are correlated, it is possible that the correlations between MS and the variables that are related to moisture, are in effect reflecting the positive relationship between MS and %OM. The relationship between MS and %OM suggests that the readings for MS are likely to be the result of magnetically charged minerals, other than Fe and Mn, being released during organic decomposition, and is further supported by the negative correlations of MS with Fe and Mn. The negative correlation between MS and pH (r_s = -.967, p<.0001) reflects the nature of the soils at Sherwood, in that it is an acidic environment with moderate MS. In addition, the negative correlation between %Clay and pH (r_s = -.491, p<.05) reflects the acidic, clay-rich soil present at Sherwood.

The positive correlations between %Clay and EC (r_s = .488, p<.05) and %Clay and moisture content (r_s = .534, p<.01) reflect the impermeable nature of a clay-rich soil and its water holding capacity, which, in turn, reflects the availability of soluble salts. Further, the negative correlations between pH and %Water (r_s = -.835, p<.0001), pH and EC (r_s = -.961, p<.0001), and pH and moisture content (r_s = -.509, p<.05) reflect the acidic soil environment and its capacity to retain moisture before and after the oxidation experiment (albeit in low quantities). The negative correlation between pH and %OM is expected, as the decomposition of OM increases the acidity of the soil, i.e. the higher the amount of OM, the lower the pH, or the more acidic the soil becomes.

Finally, the correlation between moisture content and VWC (r_s = .504, p<.05) is present in tables 4.20 and 4.21. The correlations in these tables are identical as they were taken as a control for the moisture in the soil prior to the drying out experiments. The strong positive correlation between these variables confirms the accuracy of both methods: moisture content

is a measure of soil moisture before drying out, and is as close to in-field moisture levels as possible in a laboratory environment, and VWC is a direct in-field reading of the soil moisture content at Sherwood.

4.5.2 Soil Micromorphology

Soil micromorphological analyses were carried out for each experiment group: oven dried, air dried and control, with particular focus on microstructure, relative porosity, iron oxide deposition, and organic material (appendix F). The descriptions follow Bullock *et al.* (1985) and Stoops (2003) and the coarse-fine limit for the soils at Sherwood is set at 20µm. N/A for the O horizon in both the winter oven dried experiment group and the spring control group indicate the absence of this horizon in the samples collected. I will first provide a brief description of the soil microstructure and porosity, followed by more detail on iron oxide deposition and organic material.

4.5.2.1 Microstructure and Porosity

The soil profile at Sherwood includes five horizons and the fine fabric components are described as follows: O horizon, which consists of cellular organic material along with some humified granules with predominantly channel voids; H horizon, which consists of humified organic granules with a granular to crumb structure and packing voids and/or vughs; Ae horizon, which consists of iron-rich silty clay and a channel microstructure with stipple speckling and grano- and poro-striations; Bts horizon, which consists of a channel microstructure and iron-rich silty clay, which is randomly oriented and is present as coatings on grains and channel voids; and finally, B/C horizon, which is a channel to crumb structure with silty clay, most often randomly striated and as coatings around grains, and sometimes as coatings on channels and vughs. This is typical of a brown podzolic soil with evidence of eluviation and illuviation of iron-rich clay, and the movement of humic material down the soil profile. The dominance of channel voids in the profile suggests the presence of roots and rootlets, while the subangular blocky structure of the Ae and Bts horizons suggests shrink-swell processes within these clay-rich soils. The crumb structure (0.5-3cm peds), which dominates the B/C horizon, suggests disturbance, although it was noted in the field that this horizon was the most friable and contained many large rocks (10-50cm in diameter).

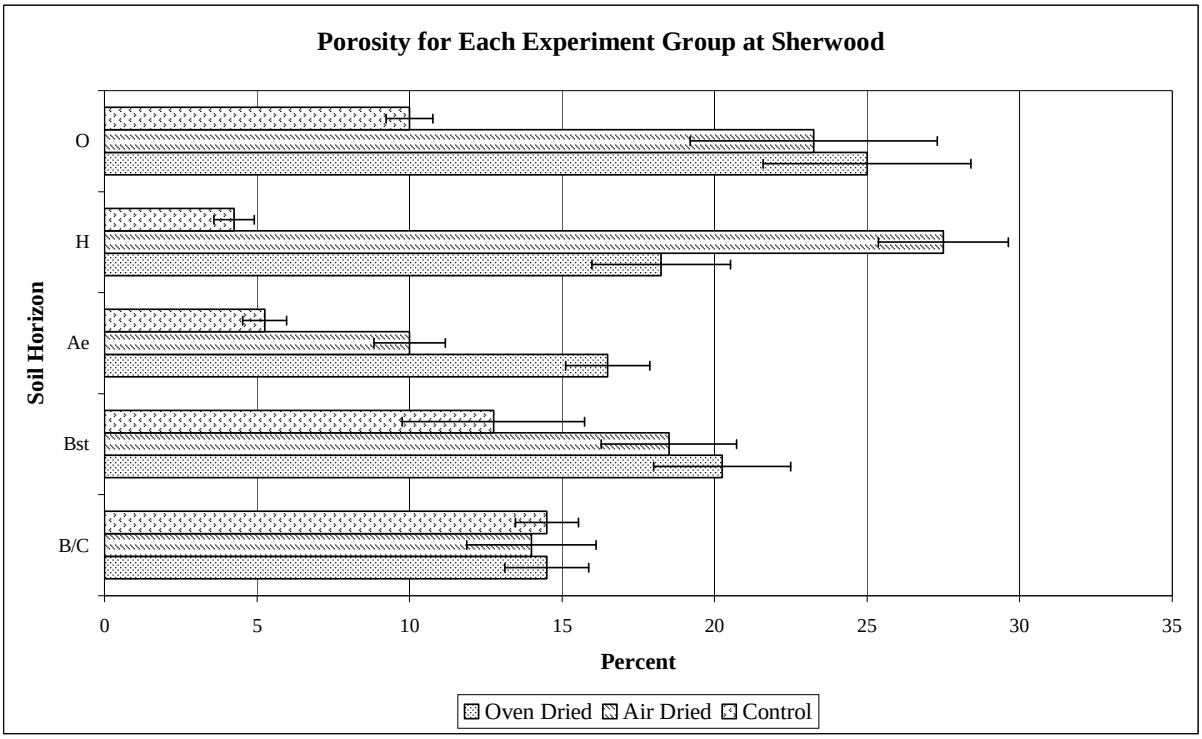


Figure 4.70. Mean porosity (%) and seasonal variation (error bars) for the soils at Sherwood for all experiment groups.

The percentage of porosity in the soil at Sherwood varies both seasonally and between experiment groups (figure 4.70). Overall, the porosity of the soil increases with the oxidation experiments, suggesting that the organic and clay-rich nature of the soil is affected by both rapid and slow oxidation. In all but the H horizon, rapid oxidation has a greater effect on porosity than slow oxidation. The greater effect the air dried experiment had on the H horizon remains unclear but suggests that humic material is more susceptible to slow oxidation than rapid oxidation. The seasonal variation present in all experiment groups most likely reflects the seasonal variation in rainfall. The limited variation between the experiment groups in the B/C horizon most likely reflects the lower quantity of clay present here (figure 4.62), providing a soil that is more freely draining than the upper, more clay-rich horizons.

4.5.2.2 Iron Oxide Deposition

The iron oxide deposition at Sherwood includes iron nodules, staining, coatings, and the replacement of organic material by iron. Although iron pans are typically found in podzols, there are no pans present at Sherwood, which suggests the podzolic process is in its infancy. There is some variability between experiment groups for iron coatings of grains and voids, as well as seasonal variability (figure 4.71). This most likely reflects the seasonal variation in

rainfall at Sherwood and the natural variability of the soil environment. The pattern of distribution of iron coatings down profile suggests that illuviation is active at Sherwood and is expected, given the podzolic nature of the soils. The lack of coatings present in the O horizon is due to the lack of minerals present and the extremely high quantities of organic material.

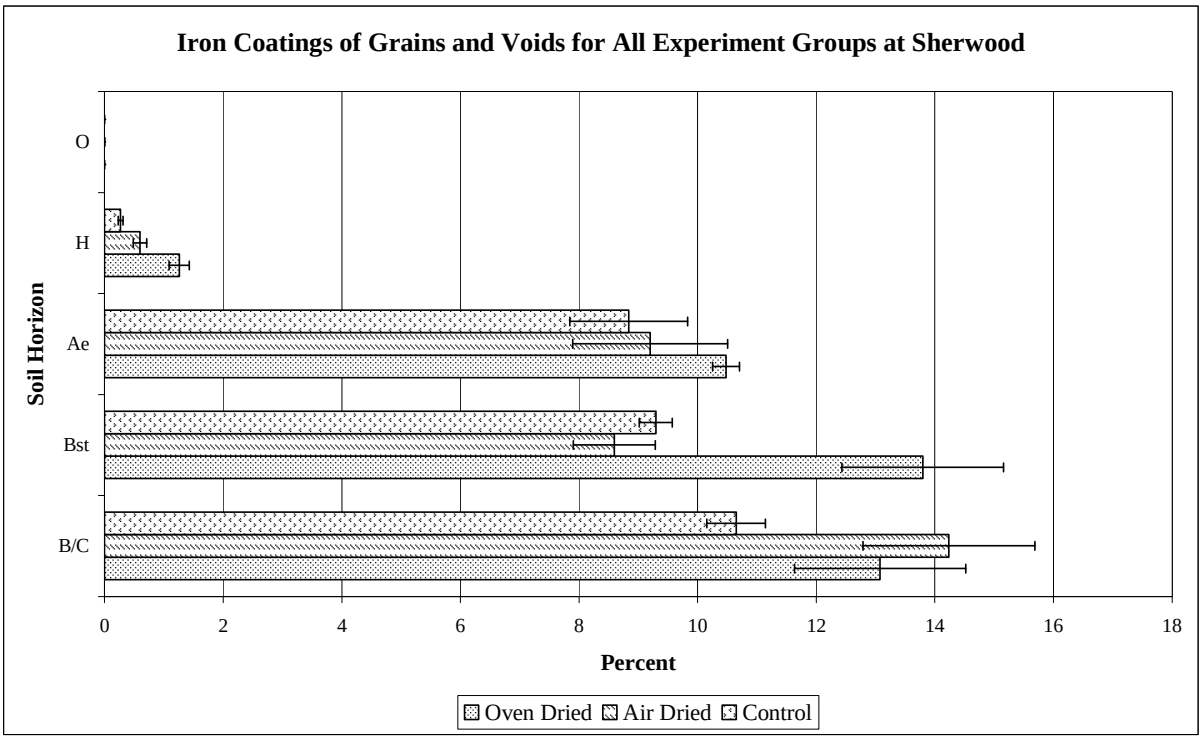


Figure 4.71. Mean percentage of coatings and seasonal variation (error bars) for all experiment groups at Sherwood.

The replacement of organic material by iron oxide is most prevalent in the upper horizons at Sherwood, and most likely reflects the processes involved in the decomposition of organic material (table 4.22). In addition, it is possible that the respiration and consumption activities of micro-organisms are responsible for cycles of reducing and oxidising conditions within these layers, providing an ideal environment for iron replacement to occur. There is little variation between experiment groups, or seasonally, which is expected as this process is not likely to be affected by the oxidation experiments. The lack of seasonal variation supports the biotic nature of the redox processes involved in the soils at Sherwood.

Table 4.22. Results for the percentage of iron replacement of organic matter, as identified through soil micromorphological analysis.

Sample Number		Soil Horizon	Replacement		
			Frequency	Minimum (µm)	Maximum (µm)
October 2003	**1.1**	O	■■■■■	117	1250
	1.1	H	■■	42	350
	1.1	AE	■	42	42
	1.2	Bst	■	150	233
	1.3	B/C	■	33	67
	2.1	O	■■■■■■■■	92	708
	2.1	H	■■■■	133	583
	2.1	AE	■	75	92
	2.2	Bst	■	17	83
	2.3	B/C	■	75	75
	3.1	O	■■■■	187	1167
	3.1	H	■	25	233
	3.1	AE			
	3.2	Bst	■	50	55
	3.3	B/C	■	17	83
January 2004	**1.1**	N/A	N/A	N/A	N/A
	1.1	H	■	25	25
	1.1	AE	■	125	242
	1.2	Bst			
	1.3	B/C	■	125	158
	2.1	O	■■■■■■	150	575
	2.1	H	■■■	67	608
	2.1	AE	■	42	258
	2.2	Bst	■	8	42
	2.3	B/C	■	92	233
	3.1	O	■■■	133	542
	3.1	H	■	57	233
	3.1	AE	■	8	83
	3.2	Bst	■	58	233
	3.3	B/C	■	58	92
April 2004	**1.1**	O	■■	82	492
	1.1	H	■■	192	303
	1.1	AE	■	17	50
	1.2	Bst	■	42	42
	1.3	B/C	■■	108	325
	2.1	O	■■■■■	167	1125
	2.1	H	■■■	150	425
	2.1	AE	■	17	117
	2.2	Bst	■	108	217
	2.3	B/C	■	193	242
	3.1	N/A	N/A	N/A	N/A
	3.1	H	■	83	148
	3.1	AE			
	3.2	Bst			
	3.3	B/C	■	67	133
July 2004	**1.1**	O	■■■■■	142	1067
	1.1	H	■■■	133	808
	1.1	AE			
	1.2	Bst	■■	55	408
	1.3	B/C	■	50	550
	2.1	O	■■■■■	140	975
	2.1	H	■■	137	533
	2.1	AE	■	167	167
	2.2	Bst	■	58	200
	2.3	B/C			
	3.1	O	■■■■	150	675
	3.1	H	■	200	283
	3.1	AE	■	42	42
	3.2	Bst	■	233	313
	3.3	B/C			

Key: ■ <2%, ■■ 2-5%, ■■■ 5-10%, ■■■■ 10-20%, ■■■■■ 20-30%, ■■■■■■ 30-40%, ■■■■■■■ 40-50%, ■■■■■■■■ 50-60%, ■■■■■■■■■ 60-70%

Iron nodules and iron staining are two types of iron oxide deposition that reflect different rates of oxidation; therefore, these two variables are the most likely to be affected by the oxidation experiments. In figure 4.72 iron nodules predominate over iron staining, and as this graph shows the results for the oven dried experiment, this result is expected. Conversely, the results for the air dried experiment show that iron staining is more dominant than iron nodules (with the exception of the humic horizon) reflecting slow oxidation (figure 4.73). The increase of nodules in the humic horizon could reflect the advance stage of decomposition of organic matter in the layer and an increase in microbial activity. A similar iron oxide deposition pattern is reflected in the control group (figure 4.74), which suggests that the soils at Sherwood are more prone to slow oxidation processes than rapid oxidation processes. Given the podzolic nature of the profile at Sherwood, the predominance of iron staining supports the preliminary stages of podzolisation, which is a long-term soil formation process involving oxidation, organic decomposition and leaching.

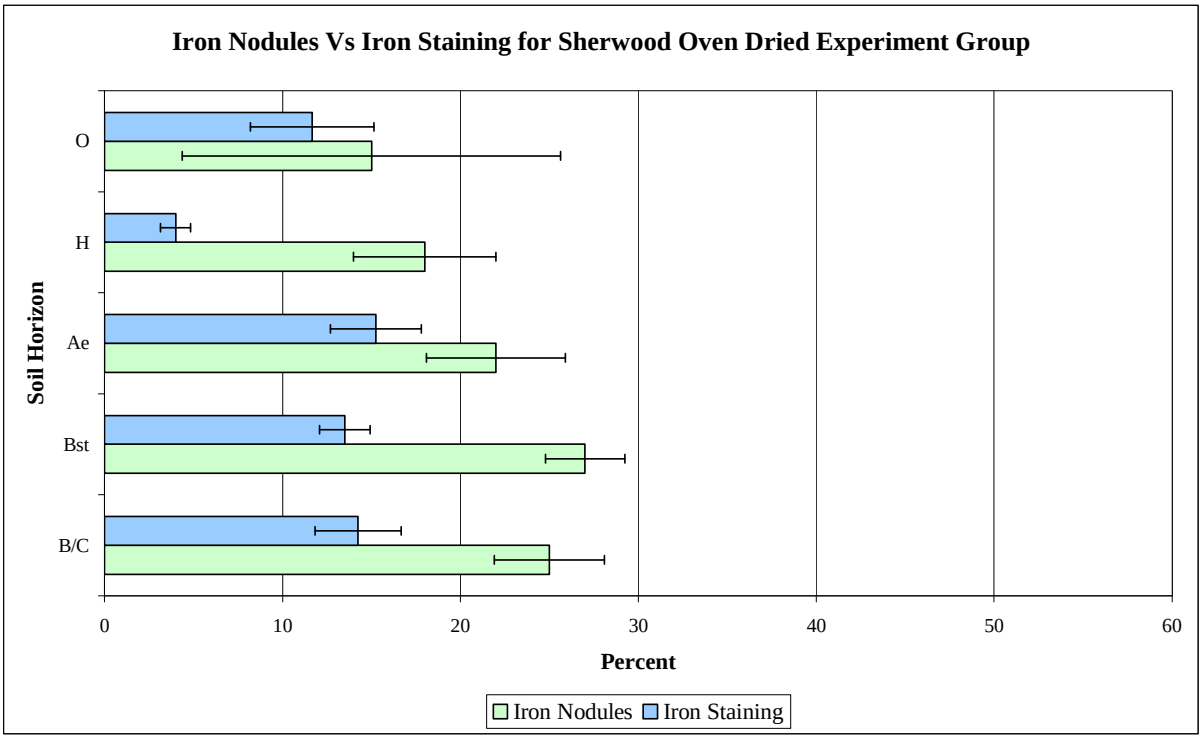


Figure 4.72. Mean percentage of iron nodules and iron staining, and the seasonal variation (error bars) for the oven dried experiment group at Sherwood.

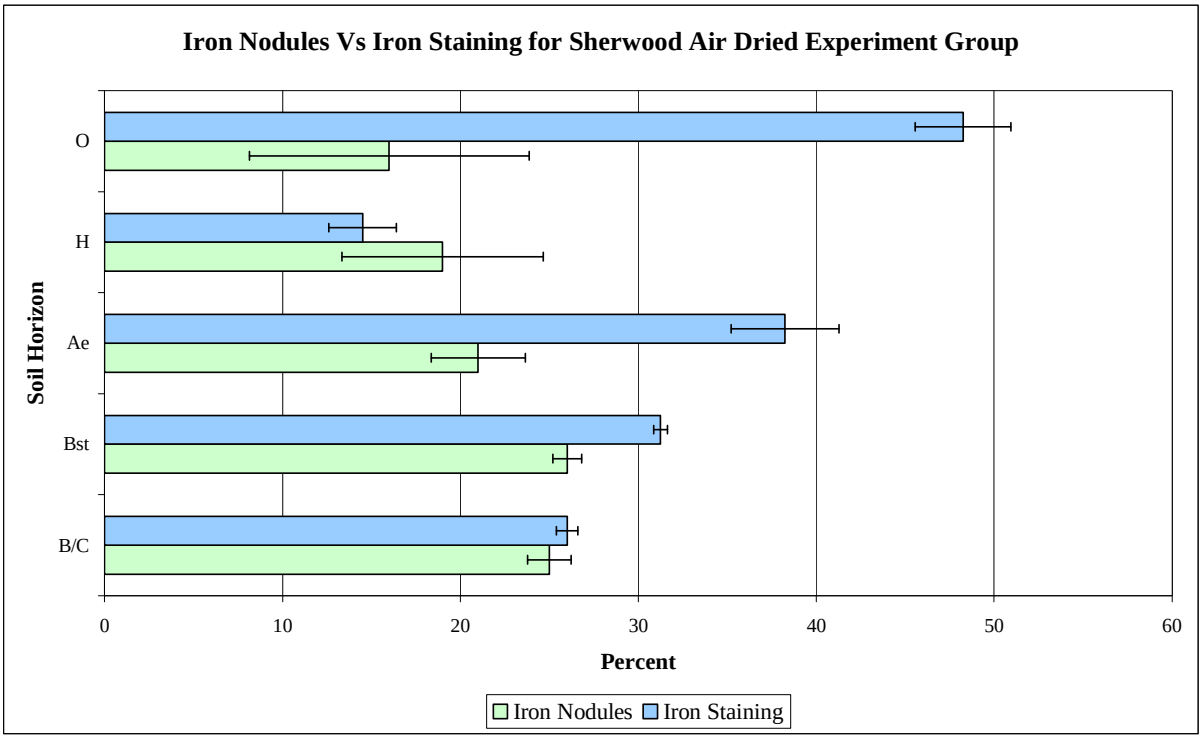


Figure 4.73. Mean percentage of iron nodules and iron staining, and the seasonal variation (error bars) for the air dried experiment group at Sherwood.

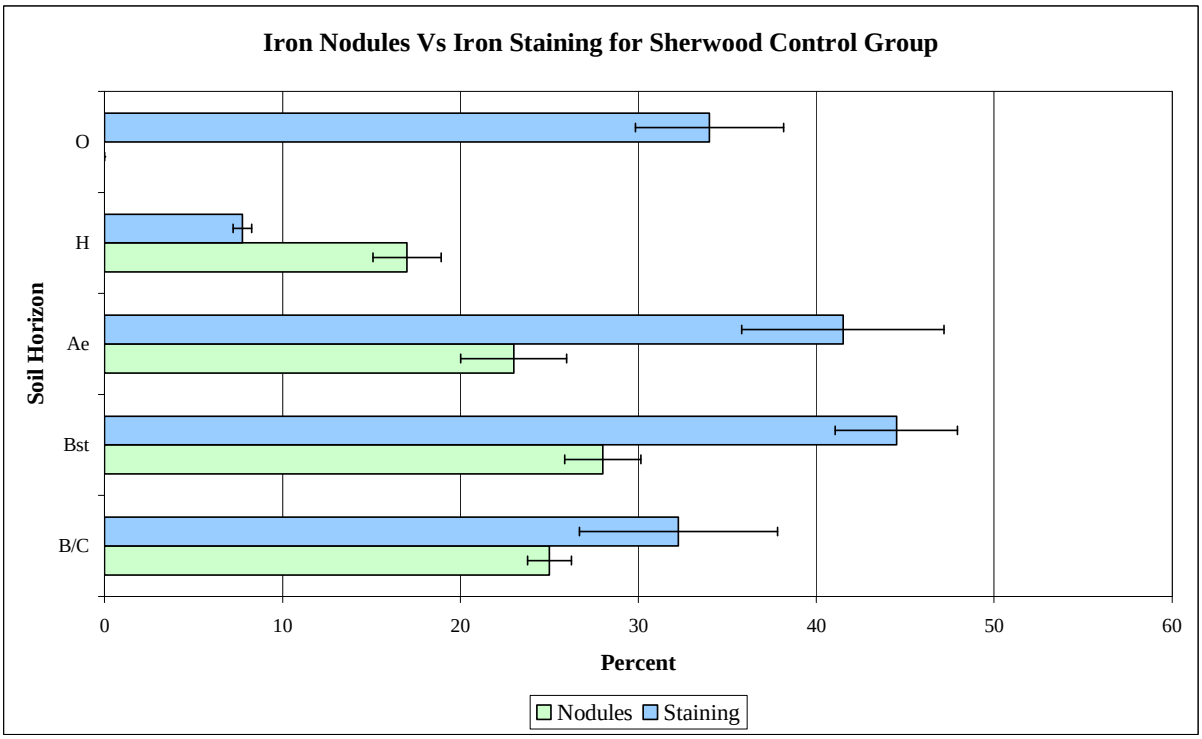


Figure 4.74. Mean percentage of iron nodules and iron staining, and the seasonal variation (error bars) for the control group at Sherwood.

4.5.2.3 Organic Material

Table 4.23 presents the percentage frequencies and preservation state for the organic material identified through soil micromorphological analysis. In addition to the frequencies and the state of preservation of the organic material, the size range for celled material, and whether or not the organic material is associated with iron oxide, is also noted (appendix F).

The distribution of fine organic punctuations down the soil profile at Sherwood reflect the podzolic processes that are occurring, with this fine organic fraction (<1µm) leaching from the upper horizons and being deposited in the lower horizons. The distribution pattern for charcoal (both <100µm and >100µm) is similar. Amorphous organic material (>1µm) is in higher proportions in the upper horizons than in the lower horizons, as are the celled organic material. The celled organic material is more prevalent in the air dried experiment group and the control group than in the oven dried experiment group. This suggests that rapid oxidation has had a greater effect on the preservation of the organic material than slow oxidation. There appears to be little seasonal variation for the amorphous organic material, the charcoal, and the celled organic material. The degree of decomposition of the celled organic material is in the early stages in the upper horizons but becomes more advanced in the lower horizons. There is an abundance of plectenchyma present with slight increases in the Ae and Bts horizons, although there does not appear to be distinct variations either seasonally or between experiment groups. Pollen is present in small amounts in the autumn and winter samples only, with slightly higher proportions in the control group. This suggests that in spite of the acidic conditions, the soil environment at Sherwood is not conducive to the substantial preservation of pollen.

Table 4.23. Percentage of organic material for Sherwood identified through micromorphological analysis.

Sample Number		Soil Horizon	Amorphous		Charcoal		Celled			Plectenchyma (Fungi)	Pollen
			Punctuations	Matter	< 100um	> 100um	Lignified	Parenchymatic	Phlobaphene		
October 2003	1.1	O	■■■	■■■■■■			■■■ 1-3	■■■■■ 1-3	■■■■■ 1-3		
	1.1	H	■■■	■■■■■■		■	■■ 1-3	■■ 1-5	■■ 1-3	■ 5	
	1.1	Ae	■■■■■	■■■■■	■	■		■ 3	■ 3	■■■ 3-5	
	1.2	Bst	■■■■■	■■■■■	■■		■ 1-3	■ 3	■ 3	■■ 3-5	■
	1.3	B/C	■■■■■■	■■■■■■	■	■		■ 1-3	■ 1-3	■ 3	■
	2.1	O	■■■	■■■■■■	■■		■■■ 1-3	■■■■■ 1-3	■■■■ 1-3	■ 3-5	
	2.1	H	■■■	■■■■■	■■	■	■ 1-3	■■■■ 1-3	■■ 1-3	■■ 3-5	
	2.1	Ae	■■■■■■	■■■■■	■■■	■	■ 1-5	■ 1-5	■ 3	■■■ 3-5	
	2.2	Bst	■■■■■■	■■■■■	■■■	■		■ 1-3	■ 1-3	■■ 3-5	■
	2.3	B/C	■■■■■■	■■■■	■■■	■	■ 4	■ 3	■ 4	■■■ 3-5	■
	3.1	O	■■■■	■■■■■■	■■	■	■■■ 1-3	■■■■■ 1-3	■■■■ 1-3	■ 3-5	
	3.1	H	■■■■	■■■■■■■■■	■■■	■	■ 1-3	■■■ 1-3	■■■ 1-3	■ 3-5	
	3.1	Ae	■■■■■■■	■■■■■	■■■	■		■ 3	■ 3	■■ 3-5	
	3.2	Bst	■■■■■■	■■■■■	■■■	■		■ 3		■■ 3-5	■■
	3.3	B/C	■■■■■■	■■■■■	■■■	■	■ 3	■ 1-3	■ 1-3	■ 3-5	■■
January 2004	1.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	1.1	H	■■■■■■■	■■■■■■			■ 1-5	■ 3-5	■ 3	■■■ 3-5	
	1.1	Ae	■■■■■■■	■■■■■	■■■	■	■ 3	■ 4-5		■■ 3-5	
	1.2	Bst	■■■■■	■■■■	■■	■				■■■ 3-5	■
	1.3	B/C	■■■■■	■■■■■	■■■■	■■		■ 1-3	■ 1-3	■ 4-5	■
	2.1	O	■■■	■■■■■■	■■■	■	■■■ 1-3	■■■■■■ 1-3	■■■■■ 1-3		
	2.1	H	■■■■■■	■■■■■■■■	■■■	■■	■■■■ 1-3	■■■■■ 1-3	■■■■■ 1-3	■ 3-5	
	2.1	Ae	■■■■■■■■	■■■■■	■■■■	■	■ 1-3	■ 1-3	■ 1-3	■■■■ 3-5	
	2.2	Bst	■■■■■■	■■■■■	■■■			■ 1-3	■ 1-3	■■ 3-5	■■
	2.3	B/C	■■■■■■	■■■■■	■■■	■	■ 1-3	■ 1-3	■ 1-3	■■ 3-5	■
	3.1	O	■■■■■■	■■■■■■■■	■■■■■	■■■	■■■■ 1-3	■■■■■ 1-3	■■■■ 1-3		
	3.1	H	■■■■■■	■■■■■■■■	■■■■	■■	■■ 1-3	■■■■ 1-3	■■■ 1-3	■■ 3-5	
	3.1	Ae	■■■■■■■	■■■■■	■■■■	■	■ 1-3	■ 1-3	■ 1-3	■■■ 3-5	
	3.2	Bst	■■■■■■■	■■■■■	■■■■	■		■ 1-3	■ 1-3	■■■ 3-5	■■
	3.3	B/C	■■■■■■	■■■■■	■■■	■		■ 1-3	■ 1-3	■■ 3-5	■■■
April 2004	1.1	O	■■■■	■■■■■■■■	■■■■	■	■■ 1-3	■■■■■ 1-3	■■■■ 1-3		
	1.1	H	■■■■■■	■■■■■■■■	■■■■	■	■ 1-3	■■■ 1-3	■■ 1-3	■■ 3-5	■
	1.1	Ae	■■■■■■	■■■■■	■■■■	■■		■ 3		■■■ 3-5	
	1.2	Bst	■■■■■■■	■■■■■	■■■	■■				■■■ 3-5	
	1.3	B/C	■■■■■■■	■■■■■	■■■	■■	■ 1-3	■ 1-3	■ 1-3	■ 3-5	
	2.1	O	■■■■	■■■■■■■■	■■■	■	■■■■ 1-3	■■■■■■ 1-3	■■■■ 1-3		
	2.1	H	■■■■	■■■■■■■■	■■■■	■	■ 1-3	■■■■ 1-3	■■■ 1-3	■ 3-5	
	2.1	Ae	■■■■■■■	■■■■■	■■■■	■■	■ 1-3	■ 1-3	■ 1-3	■■ 3-5	
	2.2	Bst	■■■■■■■	■■■■■	■■■	■				■■■ 3-5	
	2.3	B/C	■■■■■■	■■■■	■■	■		■ 1-3	■ 1	■ 3-5	
	3.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3.1	H	■■■■■	■■■■■■■■	■■■■	■■		■■■ 1-3	■■ 1-3	■ 3-5	
	3.1	Ae	■■■■■■■	■■■■■	■■■	■	■ 1-2	■ 1-3	■ 1-3	■■■ 3-5	
	3.2	Bst	■■■■■■■	■■■■	■■■	■	■ 1-2	■ 1-3	■ 1-2	■■■ 3-5	
	3.3	B/C	■■■■■■■	■■■■	■■■■	■	■ 1-3			■■ 3-5	
July 2004	1.1	O	■■■■■	■■■■■■■■■	■■■■	■	■■■■ 1-3	■■■■■ 1-3	■■■ 1-3		
	1.1	H	■■■■■	■■■■■■■■	■■■■	■■	■ 1-3	■■■ 1-3	■■ 1-3	■ 3-5	
	1.1	Ae	■■■■■■■■	■■■■■	■■■■	■■	■ 1-3	■ 1-3	■ 1-3	■■ 3-5	
	1.2	Bst	■■■■■■■	■■■■■	■■■■	■		■■ 1-3	■■ 1-3	■■■ 3-5	
	1.3	B/C	■■■■■■■	■■■■■	■■■■	■	■ 1-3	■ 1-3	■ 1-3	■ 3-5	
	2.1	O	■■■■■	■■■■■■■■■	■■■		■■■■ 1-3	■■■■■ 1-3	■■■■ 1-3		
	2.1	H	■■■■■■	■■■■■■■	■■■■	■■	■ 1-3	■■■■ 1-3	■■■ 1-3		
	2.1	Ae	■■■■■■■■	■■■■■	■■■■	■■		■ 1-3	■ 1-3	■■ 3-5	
	2.2	Bst	■■■■■■■■	■■■■■	■■■	■		■ 1-3	■ 1-3	■■ 3-5	
	2.3	B/C	■■■■■■■■	■■■■■	■■■■	■■				■■ 3-5	
	3.1	O	■■■■■	■■■■■■■■	■■■		■■■ 1-3	■■■■■■ 1-3	■■■■■ 1-3		
	3.1	H	■■■■■■	■■■■■■■■■	■■■■	■	■ 1-3	■■■■ 1-3	■■■ 1-3	■■■ 3-5	
	3.1	Ae	■■■■■■■■	■■■■■■	■■			■ 1	■ 1	■■■ 3-5	
	3.2	Bst	■■■■■■■■	■■■■■■	■■■	■	■ 1-3	■ 1-3	■ 1-3	■■■ 3-5	
	3.3	B/C	■■■■■■■■	■■■■■	■■■					■■ 3-5	

Key: ■ <2%, ■■ 2-5%, ■■■ 5-10%, ■■■■ 10-20%, ■■■■■ 20-30%, ■■■■■■ 30-40%, ■■■■■■■ 40-50%, ■■■■■■■■ 50-60%, ■■■■■■■■■ 60-70%

Key to preservation of organic material: 1 = fresh; 2 = yellow; 3 = red-brown; 4 = brown; 5 = black

4.5.3 CDB for a Brown Podzolic Soil

The bulk and micromorphological data reflect the properties of a typical brown podzolic soil with evidence of eluviation/illuviation processes including low EC readings, the distribution pattern of iron and manganese down the soil profile, along with coatings of grains and voids. Further, the MS readings show that the type of iron present is not highly magnetic; the source of these readings is most likely the organic component of the soil and the magnetic minerals that are released during the decomposition of the plant remains.

The comparative database (CDB), as represented by the two graphs below (figures 4.75 and 4.76), was formed by combining the bulk and soil micromorphological data for the experiment groups at Sherwood. These graphs highlight the variables that are most likely to provide the best representation of the oxidation environment within the soil, in a way that is functional and clear as a reference guide to gauging preservation.

Given the limited seasonal variation for each of the bulk and micromorphological analyses, the means for each variable have been used to formulate the graphs in figures 4.75 and 4.76 in reference to their soil depth and soil horizon. For each figure, a sedimentological key is provided to represent the soil profile at the site, and the corresponding bulk and soil micromorphological results are mapped out in accordance with their context in the soil profile. Two variables from the soil micromorphological analyses have been used for these graphs: iron nodules and iron staining, as these variables prove the most informative for determining the oxidation and/or hydrological environment for a brown podzolic soil such as Sherwood.

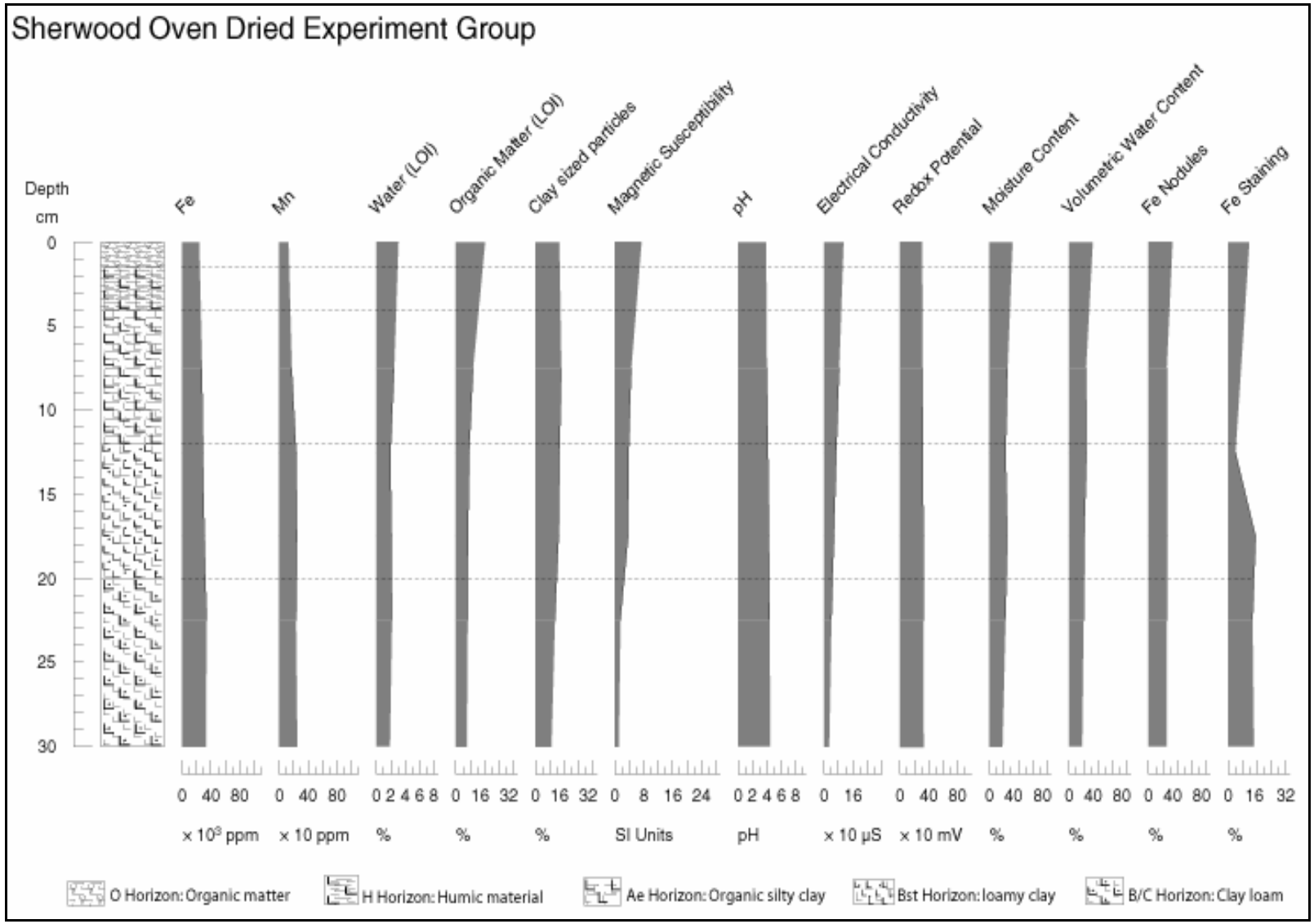


Figure 4.75. The comparative database (CDB) for the Sherwood oven dried experiment group.

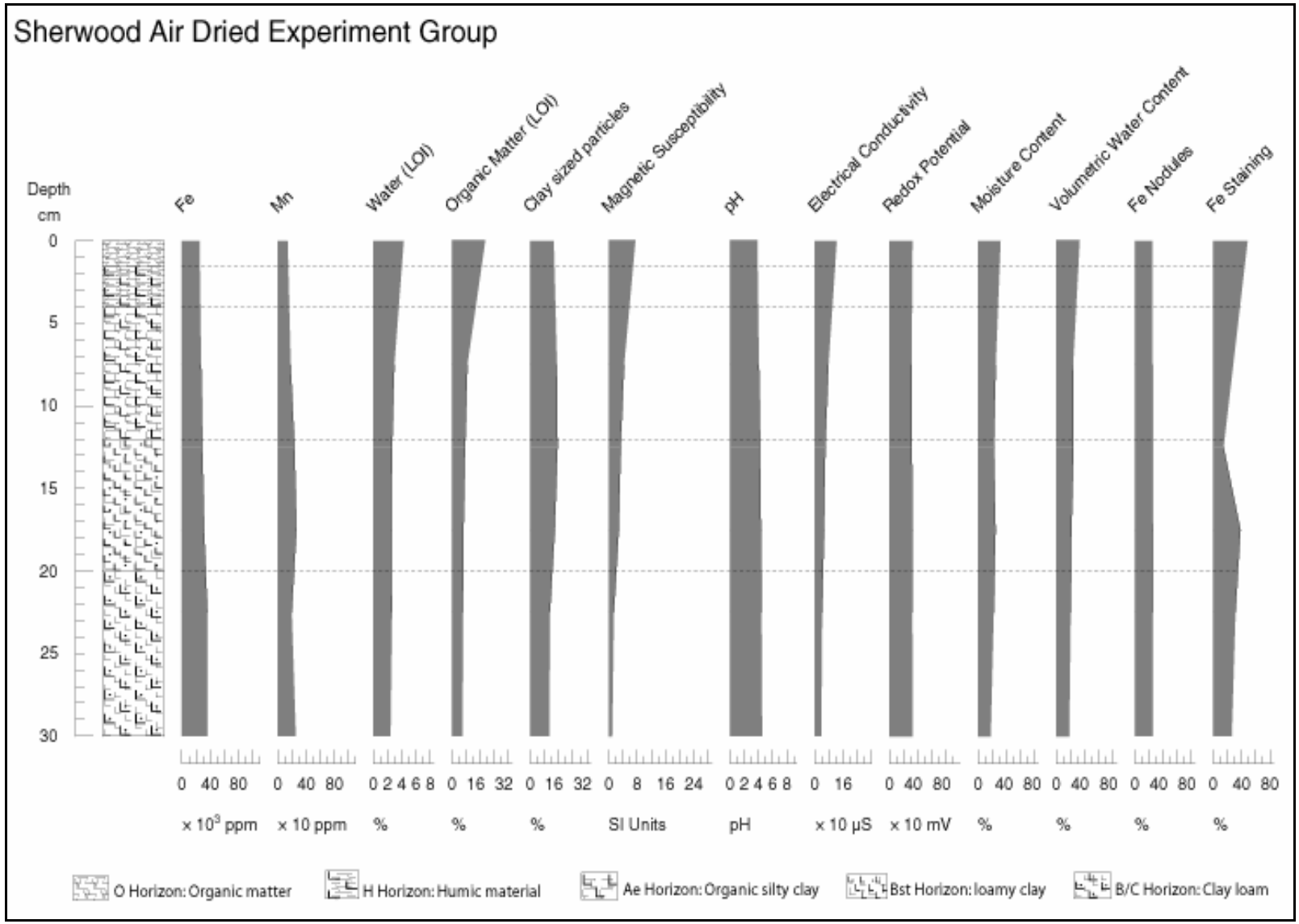


Figure 4.76. The comparative database (CDB) for the Sherwood air dried experiment group.

The bulk analyses data for Sherwood reveal very little variation between experiment groups, with the exception of %Water, suggesting that the air dried experiment group retained slightly more moisture during the oxidation process than the oven dried experiment group. This is most likely due to the variations in atmospheric moisture to which the air dried group was exposed. There is significant variation between experiment groups for iron staining and iron nodules, with a higher proportion of nodules to staining in the oven dried experiment group, and a higher proportion of staining to nodules in the air dried experiment group. This variation reflects distinct differences in iron oxide deposition directly related to the rate of oxidation of the soil environment. **Rapid** oxidation increases the amount of iron **nodules** present in the soil and **slow** oxidation increases the amount of iron **staining** in the soil. Consequently, the deposition of iron nodules and iron staining can be used as a proxy for determining the rate of oxidation in the soil environment. The effect that this oxidation has on organic material for a brown podzolic soil is most evident from the soil micromorphological analyses. The prevalence of celled organic material in the air dried group compared to that of the oven dried group, suggests that rapid oxidation has a greater effect on the preservation of organic material than slow oxidation. However, the preservation condition of the celled organic material present in both experiment groups is in the early stages of decomposition, but does become more decomposed down profile, suggesting that given time, the oxidation and leaching processes involved in the slow progress of podzolisation will have more devastating effects on the preservation of the organic material present at the site.

4.6 SUMMARY

The identification of a sensitive indicator of oxidation within the soil environment is essential to predict the effects of oxidation on organic material. Iron oxide is an ideal indicator as it is ubiquitous and reacts sensitively to changes in the oxidising conditions within the buried environment. With this in mind, oxidation experiments were carried out on soils from sites with four different soil/geology types. The effects of these experiments were measured using a suite of bulk analyses, as well as soil micromorphology. While the bulk analyses allowed the quantification of iron and the variables which influence it, the soil micromorphological analyses provided a context in which to identify signatures of iron oxide deposition within the soil.

This chapter presented the results for the micromorphological and bulk analyses for each experiment group and site, beginning with Over, followed by Wandlebury and Savernake, and finishing with Sherwood. While the bulk analyses for each of the sites revealed little variation either seasonally or, more importantly, between experiment groups, the data obtained from these analyses have been very useful in quantifying the iron present in the soil, as well as identifying likely sources of iron, thereby highlighting the processes by which the iron oxide deposition occurred. In addition, data from the bulk analyses have provided information about other processes that occurred in the soils, such as leaching. Likewise, the soil micromorphological analyses have provided information about soil processes, such as eluviation/illuviation and reducing-oxidising cycles, along with evidence of microbial activity and bioturbation. In addition, the variations in organic decomposition have been identified, and where possible, related directly to different types of iron oxide deposition and oxidising conditions. These analyses have highlighted two variables in particular, which are the most informative for determining the oxidising conditions present in the buried environment, namely iron staining and iron nodules. For each soil/geology type presented in this research, the prevalence of iron staining in the soil is indicative of a slow oxidising environment, whereas the prevalence of iron nodules in the soil is indicative of a rapid oxidising environment.

The analyses for Over, an alluvial brown earth under arable cultivation, reveal that the soil profile has been severely leached due to the rapid lowering of the groundwater table ahead of gravel extraction in the vicinity of the site. This leaching has left very little organic material in the soil, and therefore, the results for the organic material, identified through soil

micromorphology, are limited in scope for determining the effects the oxidation experiments have on the preservation of organic material at Over. However, given the effects of the rapid introduction of oxygen via the water abstraction at Over, I suggest that rapid oxidation of this magnitude is far more detrimental to organic material than slow oxidation of soil via natural fluctuations of the groundwater table, a condition which existed at Over prior to water abstraction and associated gravel extraction.

The analyses for Wandlebury, a typical rendzina under a pastoral landscape, reveal that the soil is rich in organic material and that microbial activity plays an important role in organic decomposition. In addition, the bulk analyses data reveal that the soils at Wandlebury have unusually high magnetic susceptibility, which cannot be attributed to the presence of iron alone. Other minerals, such as manganese, are likely to be contributors to these readings along with those minerals released during organic decomposition, such as copper and cobalt, which have high magnetic susceptibility. Further, the past land use at Wandlebury may have enhanced the magnetic susceptibility of the soil, with evidence of settlement occupation and associated burning (French *et al.* 2005b), converting non-magnetic Fe into more magnetic forms of Fe, such as magnetite. Although Wandlebury is an organic-rich soil, the effects of the oxidation experiments on the preservation of the organic material cannot be clearly demarcated, as other factors, such as redox processes via microbial respiration and consumption, have had significant influences on the preservation of organic material at this site, with the presence of iron replacement of organic material, which preserves the cell structure of the organic material.

The analyses for Savernake, an argillic pelosol under an oak forest environment, have confirmed the effects of redox processes as a result of the natural fluctuations of the groundwater table. The oxidation experiments have had a significant effect on the porosity of the soil, which is expected given the clay-rich nature of the soil. The oven dried group, which represents rapid oxidation, has greater porosity than the air dried group, which represents the slow oxidation of the soils. In addition, the preservation of celled organic material present in the soils has been affected to some degree by the oxidation experiments, with more organic material being preserved in the control group than in either of the oxidation experiment groups. Given the good preservation of the control group, and that Savernake is influenced by seasonal groundwater fluctuations (slow oxidation), it can be assumed that in time, the preservation of the organic material at this site would have been more variable between the

oxidation experiments, with rapid oxidation having a greater effect than slow oxidation (cf. Welch and Thomas 1998).

Finally, the analyses for Sherwood, a brown podzolic soil under a Scots Pine forest environment, reflect the podzolisation processes present at this site. The bulk and micromorphological data have identified eluviation and illuviation processes, by the movement of fine organic punctuations down the soil profile, the prevalence of clay illuviation in the lower horizons, and the leaching of available soluble salts in the soil at Sherwood. In addition, the changes in soil porosity between experiment groups indicate that the oxidation experiments have had a significant influence on the soil environment. Generally, rapid oxidation has caused the greatest porosity of the soil, followed by slow oxidation, and the control group with the least porosity. Further, rapid oxidation has had a greater effect than slow oxidation on the celled organic material present in the soil at Sherwood. The amount of celled organic material in both the control and the air dried groups is greater than the oven dried group. As would be expected in a podzolic soil, such as Sherwood, the preservation of the organic material deteriorates down profile as a result of leaching.

While this chapter has focused on identifying and developing a tool for gauging preservation of organic material, the use and value of this database is only measured by applying it to archaeological contexts. The next chapter introduces five archaeological sites with similar soil/geology types to the CDB sites presented here, and presents the results of bulk and soil micromorphological analyses carried out on various buried soils and feature fills.

– 5 –

RESULTS PART II: INTRODUCING AN ARCHAEOLOGICAL CONTEXT

5.1 INTRODUCTION

The introduction of oxygen to an anaerobic environment is detrimental to the preservation of archaeological material data, especially organic materials and bio-archaeological data. The variation in decomposition of organic material is related to the nature of the oxidising conditions present in the buried soil environment. The development of the comparative database (CDB), as discussed in the previous chapter, uses a sensitive indicator of oxidation, iron oxide deposition, as a tool for determining the oxidising conditions present in the buried environment. Two variables in particular have proven most valuable for identifying the effects of different rates of oxidation: iron nodules and iron staining, both identified through soil micromorphological analysis. The predominance of iron nodules present in the soil represents rapid oxidation, while the predominance of iron staining in the soil represents slow oxidation (Gerrard 1992, 96; Ralston 1979, 424). Rapid oxidation reflects activities such as a rapid drop in groundwater table due to water abstraction, whereas slow oxidation reflects the natural fluctuations of the groundwater table. This chapter introduces an archaeological context for testing the effectiveness of using these distinctive patterns of iron oxide deposition as a tool for gauging the preservation of organic material on an archaeological site.

Three types of iron oxide deposition discussed in this chapter are influenced by the fluctuations of the groundwater table: iron panning, iron staining and iron nodules. Groundwater is “water that fills or saturates all the available pore space within soil or rock materials” (Rose 2004, 324). There are three main zones in the soil environment that are predominant in the presence of a fluctuating groundwater table: the saturated zone

(groundwater), the oxidised zone, and the fluctuation zone (*ibid*). The saturated zone is the anaerobic soil located below the permanent watertable; the oxidised zone is the aerobic soil located above the permanent watertable; and the fluctuation zone is the zone between the saturated and oxidised zones, which is most affected by the fluctuations of the groundwater table, often resulting in a mottled soil horizon (figure 5.1) (Gerrard 1992; Rose 2004). This mottled horizon is the result of reducing-oxidising cycles from the fluctuations in the groundwater table and, depending on the rate and frequency of these fluctuations, different types of iron oxide deposition can occur.

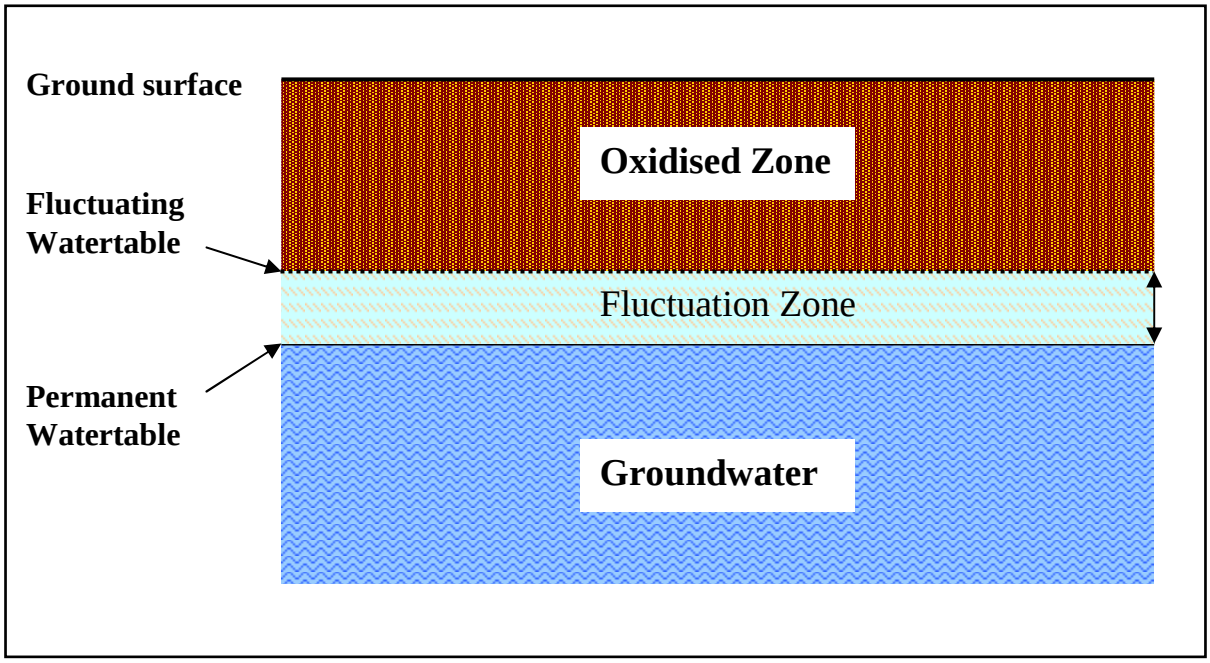


Figure 5.1. Schematic illustration of the three main zones involved in the natural fluctuation of the groundwater table.

If reducing conditions are rapidly oxidised, diffuse iron nodules form, whereas if oxygen is introduced at a slow rate, iron staining occurs (Gerrard 1992, 96; Ralston 1979, 424). Additionally, the rapid introduction of oxygen to a reducing environment (or the rapid lowering of the groundwater table) can result in advection (Welch and Thomas 1998). Advection occurs when the rapid movement of the groundwater carries away any dissolved minerals (or chemicals) in the soil solution, thereby resulting in the leaching of the soil of its nutrients, leaving any organic archaeological remains exposed to immediate oxidation and subsequent deterioration (*ibid*). The slow oxidation of an anaerobic environment (or the natural fluctuations of the groundwater table) results in diffusion (*ibid*). Diffusion is an extremely slow process, which involves the concentrations of the minerals in the soil to move

from high concentrations to low concentrations, and due to its slow process, considerable damage is less likely to occur to the organic remains present in archaeological contexts (*ibid*).

Frequent reducing-oxidising cycles, often as a result of the natural fluctuations of the groundwater table, can result in both iron replacement of organic material and iron panning (as explained in chapter 2). Both these processes can protect organic material against deterioration, the former by retaining the structure of the organic material by way of pseudomorphs, and the latter by forming a barrier around archaeological features, which prevents post depositional leaching and/or decomposition of the organic material contained within the pan.

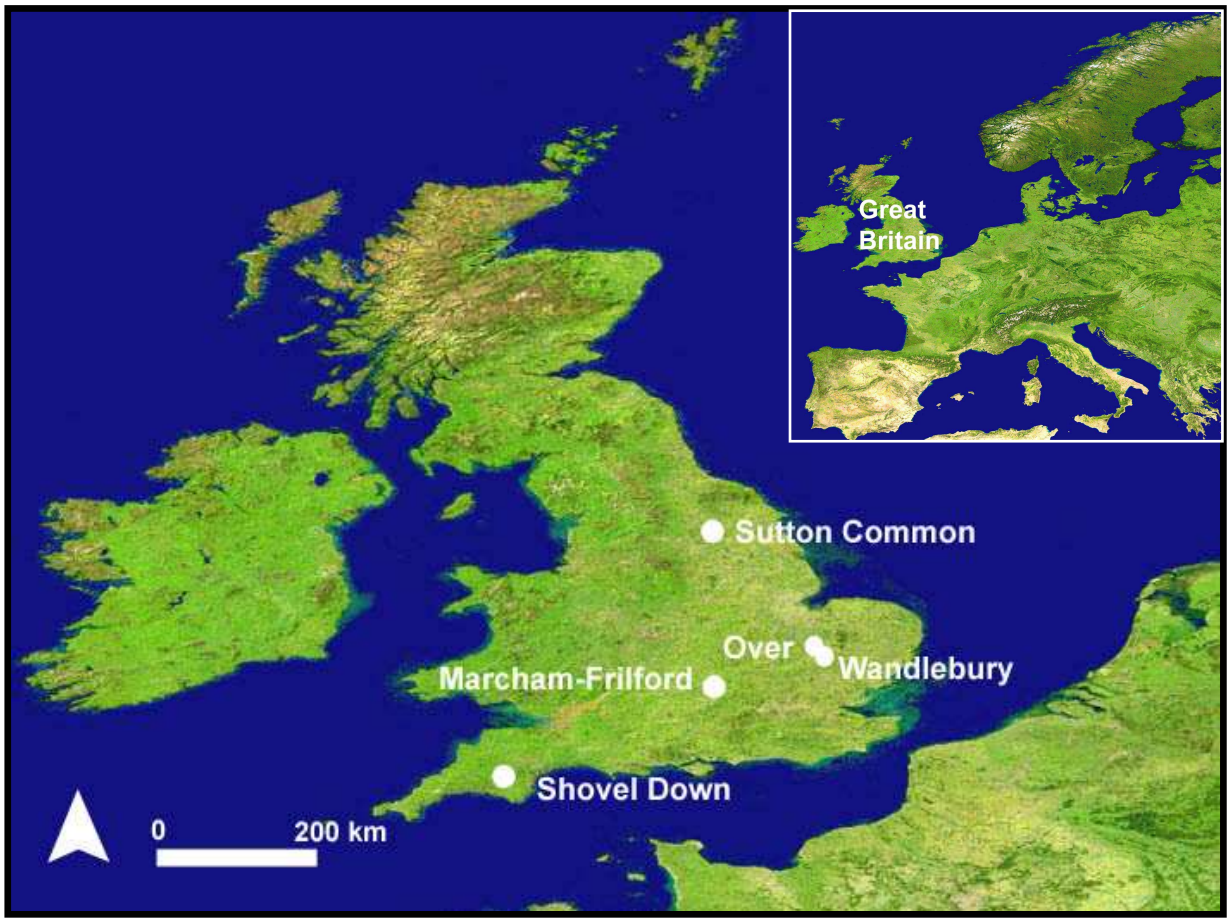


Figure 5.2. Map of the location of the five archaeological sites selected to test the effectiveness of the CDB (maps adapted from http://www.globe-images.net/europe-image.htm).

Five archaeological sites, with similar soil/geology types to the CDB sites (see chapter four), were selected and samples were collected for bulk and micromorphological analyses, following the protocols and analyses used for the development of the CDB. This chapter first introduces the sites with a brief background to each site, followed by the results of the bulk

and micromorphological analyses on a site by site basis. These sites include the Late Bronze Age enclosure at Over, the Iron Age ringwork at Wandlebury, the Romano-British site at Marcham-Frilford, the Iron Age enclosures at Sutton Common and the Bronze Age field systems at Shovel Down (figure 5.2).

5.2 LATE BRONZE AGE ENCLOSURE AT OVER

The Late Bronze Age enclosure at Over (Site 9) is situated in an alluvial floodplain of the lower Great Ouse valley in Cambridgeshire between the villages of Over and Willingham to the south and Bluntisham and Earith to the north (TL 390725) (French and Heathcote 2003). Located beneath *c.*1.5m of silty clay alluvium and oxidised peat overburden, and overlying Devensian river gravels and Oxford Clay, the site was excavated in 2004 and is part of a hydrological monitoring programme. This programme has been in place since 1994, made necessary by the gravel extraction being carried out in the vicinity of the site (figure 5.3). It aims to assess the changes in hydrology, soil structure and geochemical status before, during and after gravel extraction (French *et al.* 1999; French 2004). The Late Bronze Age enclosure is part of a rich archaeological record with artefacts, sites and cropmark evidence ranging from the Mesolithic to the Roman period (Evans and Knight 1997; French *et al.* 1999, 43). The site is currently under arable cultivation but is protected from ploughing by the thick alluvial overburden (figure 5.4).



Figure 5.3. Looking from the Late Bronze Age enclosure NE towards the gravel quarry at Over.

Prior to gravel extraction, the groundwater table was around 1.2 to 1.5m below the ground surface, but due to the water abstraction necessary to gain access to the gravel beds and allow dry sand/gravel extraction, the groundwater table has been lowered by pumping to around 5m below the surface (French 2004). This rapid drop in the groundwater table has had detrimental effects on the preservation of the archaeological and palaeoenvironmental records at Over. For example, French (2004, 3) observed that prior to the water abstraction the groundwater table was high enough to inhibit the excavation of the barrow mound and ring-ditch (Over I.20) but in the following year the watertable had dropped significantly, making it possible to excavate the site without groundwater influences. After an additional year of gravel extraction, the watertable had dropped again making the barrow an "isolated tump of land within the quarry" and dramatically reduced the soil moisture content of both the barrow and the ring-ditch fill (*ibid*).

The pre-extraction phase monitoring determined that the main influences on the groundwater table were seasonal variations in rainfall, river levels, recharge from the aquifer in the gravels and irrigation, with the an average groundwater level of about 1.5m below the surface and soil moisture content of the buried soil of about 20-50% (*ibid*). The site's pH was circum-neutral

to alkaline and redox readings showed that the sediments below the groundwater table remained waterlogged (*ibid*). However, during the extraction phase, monitoring results revealed that pH at the site had risen, becoming predominantly alkaline, the soil moisture content of the buried soil was reduced to <20% from *c.*40-60%, although the redox readings revealed that the sediments below the groundwater table remained anaerobic. Unfortunately, due to the drastic reduction in groundwater levels (*c.* 5m below the ground surface), the archaeological sediments were no longer within this anaerobic environment and suffered the effects of oxidising conditions (*ibid*).

In an attempt to counteract the effects of water abstraction on the archaeological and environmental records at Over, the quarry company (Hanson) constructed a wide bund of Oxford Clay at the southern perimeter of the site and around the whole of the first-phase gravel extraction pit, and a reed fen environment has been recreated as a Royal Society for the Protection of Birds reserve (*ibid*). As a result, the groundwater level upstream and to the south of the extraction area has recovered and is equal to the pre-extraction phase level (*ibid*). The pH remains alkaline and the redox readings remain anaerobic, although the groundwater table levels are generally well below the lowest levels of archaeological remains (*ibid*). The hydrological monitoring programme at Over continues and, the data collated from the samples collected during the excavation of Over Site 9 in 2004, will provide additional information on the effects of oxidising conditions on the preservation of organic material at Over.

Over Site 9 is situated on the east bank of a former palaeochannel of the River Great Ouse *c.* 7m OD, and is an approximately 1ha hexagonal shaped, double-ditched Late Bronze Age enclosure (*c.* 1200-1000 BC). The site includes a post-built rectilinear structure and several circular post and eaves-drip gully structures, as well as miscellaneous pits, postholes, gullies and ditches. The site is set inside a Middle Bronze Age rectilinear field system with six earlier Bronze Age barrows, three on either side. Two features from within the Late Bronze Age enclosure were chosen for micromorphological and bulk analyses along with the buried soil (figure 5.4).

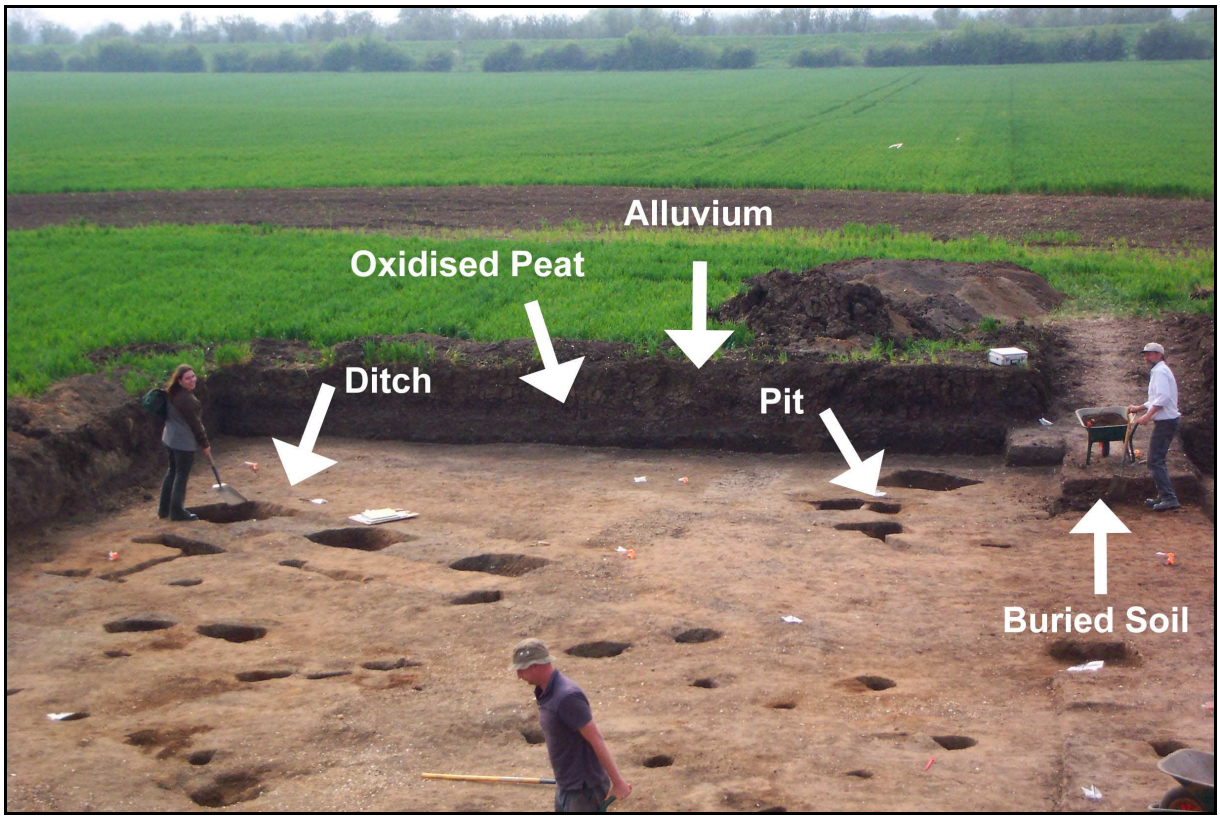


Figure 5.4. The Late Bronze Age enclosure at Over (excavated in 2004) showing the location of the samples taken from the site and the peat and alluvial overburden.

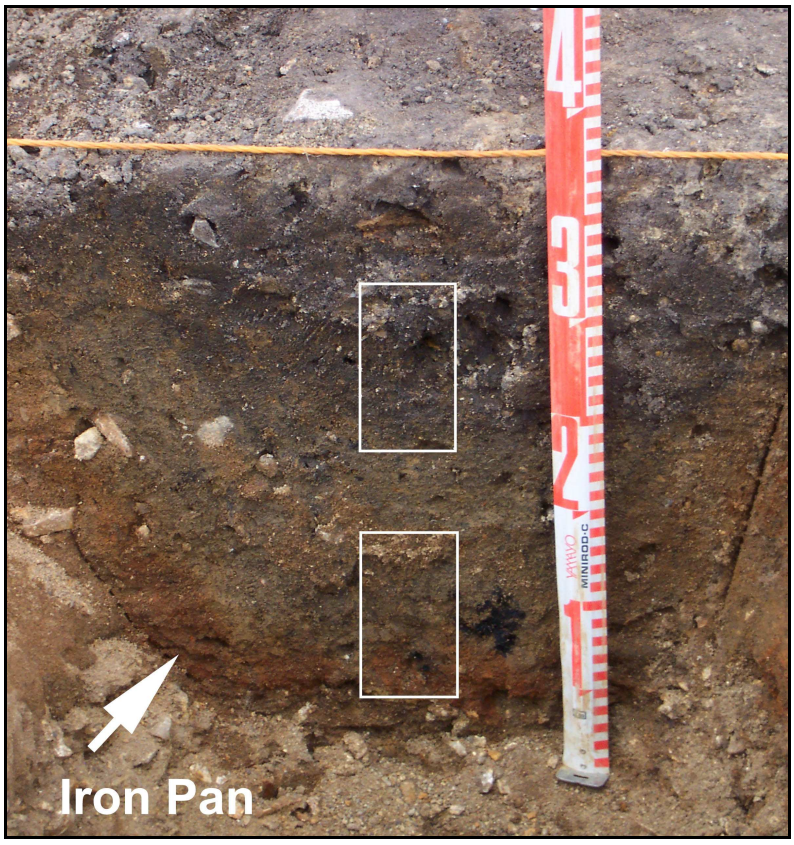


Figure 5.5. The location of the samples collected from the pit fill at Over.



Figure 5.6. The location of the samples collected from the ditch fill at Over.

In total, five micromorphological samples and five associated bulk samples for bulk analyses were collected (table 5.1): two from a pit (figure 5.5), two from a ditch (figure 5.6), and one from the buried soil beneath the peat and alluvial overburden (figure 5.4).

Table 5.1. The soil micromorphology and bulk samples collected from the Late Bronze Age enclosure at Over, along with their field description and context.

Micromorphology Sample*	Field Description and Context	Associated Bulk Sample
Over 04 TD Site 9 [9] (96) <8> a	black (organic) layer of pit fill	Over 04 TD Site 9 <10>
Over 04 TD Site 9 [9] (96) <8> b	light brown layer between black and orange layers of pit fill	Over 04 TD Site 9 <10>
Over 04 TD Site 9 [9] (98) <9>	orange layer (Fe) from pit fill	Over 04 TD Site 9 <11>
Over 04 TD Site 9 <12>	Late Bronze Age Buried Soil	Over 04 TD Site 9 <13>
Over 04 TD Site 9 [11] (107) <14>	upper sample from ditch	Over 04 TD Site 9 <16>
Over 04 TD Site 9 [11] (108) <15>	lower sample from ditch	Over 04 TD Site 9 <17>

* a and b signify separate units identified by soil micromorphology in the same sample

The photographs in figures 5.5 and 5.6 show clear iron oxide features present at the base of the pit and ditch, respectively. The features were chosen in relation to their association with obvious iron oxide deposits so as to determine the role that iron oxide has as a sensitive indicator for changes in the oxidation environment, and consequently, the effects that these changes have on the preservation of the organic material contained within the sediments. In addition to bulk and micromorphological analyses, in-field soil moisture readings were recorded for each of the contexts for each feature, the buried soil, and the alluvial overburden, using a TDR300 moisture meter.

The volumetric water content of the alluvial overburden was taken seasonally from autumn 2003 to summer 2004. The results, presented in table 5.2, show that the moisture present in the alluvium reflects the seasonal soil moisture deficit variation recorded by MORECS. This would suggest that the moisture retained within the alluvium is influenced by variations in rainfall and evaporation at Over. Overall, the level of moisture in the alluvial overburden, recorded by the moisture meter, is relatively high and remains beneficial for preventing loss of moisture via evaporation from the free-draining soils beneath.

Table 5.2. This table presents the average seasonal volumetric water content readings taken by the TDR moisture meter for the alluvial overburden recorded during sampling for the CDB at Over, and the seasonal soil moisture deficit for 2003-2004, courtesy of MORECS.

Season	Alluvial Overburden VWC (%)	Soi Moisture Deficit (mm)
Autumn	55.67	84.1
Winter	137.67	0
Spring	82.67	2.9
Summer	34.67	112.3

Although the archaeological site at Over was not originally waterlogged, its burial by peat growth and alluvial silty clay deposition has protected the archaeological integrity of the site, and prior to gravel extraction, the high watertable and the relatively impermeable nature of the alluvium has provided a good preservation environment (*ibid*).

5.2.1 Bulk Analyses Data

A suite of bulk analyses were carried out on the bulk samples collected from the Late Bronze Age enclosure at Over, which included ICP-AES for total Fe and Mn, MS, LOI for %Water

and %OM, PSD for %Clay, pH, EC and redox (table 5.3). In addition, moisture content (%) and in-field moisture readings (VWC) were recorded (table 5.3).

The results of the ICP-AES for total Fe show that the buried soil lies within the natural range of iron present in the soils at Over (table 5.3 and figure 5.7). There is an increase in Fe for each of the feature fills, and given the presence of the iron pan at the base of each of these features, the higher quantities of Fe is expected. Further, as will be seen from the micromorphological analysis, the organic-rich sediments of the fills and the subsequent decay of this organic material have added to the total Fe present within these sediments.

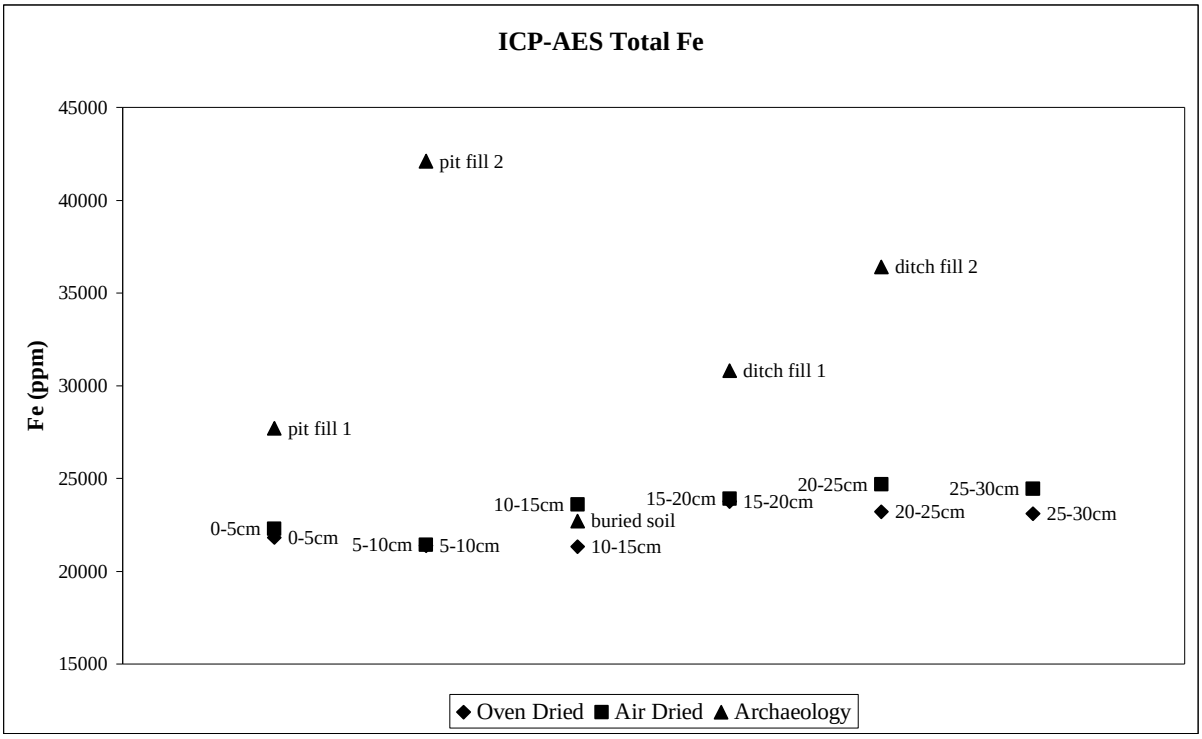


Figure 5.7. Results for total Fe for the archaeological sediments and the samples analysed for the CDB. The x-axis is absent as this graph is a histogram, i.e. the x-axis is simply the number of samples, and it is presented in the format above so as to clearly illustrate the variations in the quantity of Fe (ppm) present in each of the samples.

A similar pattern appears for total Mn, although the Mn present in the archaeological sediments is up to nine times higher than the natural Mn levels (cf. chapter 4 and appendix F). The lowest reading is from the buried soil, which remains at least twice as high as the natural Mn levels for Over (cf. chapter 4 and appendix F). In addition, the quantities of OM and clay are higher in the archaeological sediment and the MS readings are up to seven times higher than the natural soils (table 5.3, cf. appendix F). Whereas the natural soils have suffered from leaching of OM, clay and other soil nutrients, the archaeological sediments have retained this

material, and in the case of the ditch and the pit, the iron pans at the base of these features have prevented the leaching out of the soil nutrients with the rapid lowering of the groundwater table. Further, as will be discussed below, the micromorphological analyses have revealed that the feature fills and the buried soil are rich in organic material in various states of preservation, and the decomposition of this material releases plant nutrients (table 5.4), which can contribute to the high MS readings. In addition, the pit sediments contain wood ash, which suggests that some burning has occurred within the site. This may have contributed to the increase in Mn and the higher MS readings as it has been shown that burning increases the amount of total Mn present in the soils (Gonzalez Parra *et al.* 1996). In addition, burning transforms iron that may not be magnetically susceptible into magnetite, which is a highly magnetic form of iron oxide (Stucki *et al.* 1988).

The EC results are slightly higher than the natural sediments, which confirm that the archaeological sediments have not gone through the same leaching processes as the natural soils. However, the EC readings are generally low, which indicates that the main source of water in the sediments at Over is from precipitation, as rainwater generally has lower conductivity levels than groundwater (Caple and Dungworth 1997). This would attest to the current position of the groundwater table at approximately 5m below the surface. The redox results are within the natural range and indicate the presence of moderately reducing sediments (cf. Cronyn 1990, 21). The moisture content and VWC for the upper pit fill and the buried soil are consistent, with more variation in the lower pit fill and the ditch fill. The variation between the moisture content and VWC for the upper ditch fill is unclear, but the variation between moisture content and VWC, as a measure of moisture in the sediments, could be attributed to the density of the iron pan (high moisture content) and the impermeable nature of the pan (low VWC).

Table 5.3. Results for the bulk analyses carried out on the bulk samples collected from the Late Bronze Age enclosure at Over; MC = moisture content.

Sample	Context	Fe (ppm)	Mn (ppm)	%Clay (PSD)	MS (x10 $^{-8}$ (m^3/kg))	%Water (LOI)	%OM (LOI)	pH	EC	Redox	MC (%)	VWC (%)
OverTD10	Pit fill 1	27700	718	13.77	5.65	2.87	3.63	7.22	60.67	158.00	20.30	22.00
OverTD11	Pit fill 2	42100	803	14.60	7.09	2.68	3.26	7.71	65.67	154.33	22.58	15.67
OverTD13	Buried soil	22700	287	10.55	1.32	2.46	3.51	6.76	39.33	173.67	17.08	18.00
OverTD16	Ditch fill 1	30800	449	10.53	5.22	2.38	3.02	6.80	41.00	173.33	12.25	19.00
OverTD17	Ditch fill 2	36400	905	9.21	3.41	2.04	2.35	6.90	45.33	174.33	18.87	8.33

Table 5.4. Results from ICP-AES for the plant nutrients present in the samples collected from the Late Bronze Age enclosure at Over.

Over	Plant Macro-Nutrients							Plant Micro-Nutrients						
Sample Name	Al (ppm)	Ca (ppm)	Fe (ppm)	K (ppm)	Mg (ppm)	P (ppm)	S (ppm)	B (ppm)	Co (ppm)	Cu (ppm)	Mn (ppm)	Mo (ppm)	Na (ppm)	Zn (ppm)
OverTD10	7600	8900	27700	900	900	5760	300	10	9	36	718	1	200	153
OverTD11	6900	10400	42100	900	800	5620	200	10	9	29	803	1	200	118
OverTD13	7700	3700	22700	800	800	2850	300	<10	8	27	287	1	100	106
OverTD16	7100	4600	30800	800	800	4260	200	<10	9	34	449	2	200	109
OverTD17	6000	2700	36400	600	600	2730	200	<10	10	17	905	1	100	75

5.2.2 Soil Micromorphology

Soil micromorphological analyses were carried out on the samples collected from Over Site 9 following the same protocol used for the CDB sites. The results of these analyses are presented in appendix F, tables 5.5 and 5.6, and figure 5.8 below.

Sample 12, the Late Bronze Age buried soil, is an iron- and organic-rich fine sandy loam with a channel structure and illuvial silty clay coatings of grains and voids, which suggests that it is the buried lower A horizon of a typical brown earth. The silty clay coatings and fine organic punctuations suggest that the palaeosol may have been subjected to arable cultivation at some point (cf. Macphail 1998). There are significant iron coatings of channel voids (table 5.6) from the decomposition of the organic material present in the palaeosol. In addition, phytoliths are present throughout the horizon as well as some Ca-P crypto-crystalline infillings (Brothwell and Pollard 2001, 171), which are the result of the decomposition of bone, although no bone was present in the section. The majority of the organic material present in the palaeosol is amorphous punctuations and fine amorphous organic matter (table 5.5). In addition, the soil is rich in fine charcoal (<100µm) with up to 5% of coarse charcoal (>100µm).

Table 5.5. Results for the organic material identified through soil micromorphological analysis based on the protocol used for the CDB at Over.

Over	Amorphous		Charcoal <	Charcoal	Celled			Plectenchyma	Pollen
Sample Name	Punctuations	Matter	100µm	> 100µm	Lignified	Parenchymatic	Phlobaphene	(Fungi)	
Over 04 TD Site 9 [9] (96) <8> a	■■■■■■■■	■■■■■	■■■■■	■■■■		■ 1-2			
Over 04 TD Site 9 [9] (96) <8> b	■■■■■■■■	■■■■■■	■■■■■	■■■■					
Over 04 TD Site 9 [9] (98) <9>	■■■■■■■	■■■■■■	■■■■■	■■■■					■
Over 04 TD Site 9 <12>	■■■■■■■	■■■■■	■■■■	■■				■ 3-5	
Over 04 TD Site 9 [11] (107) <14>	■■■■■■■■	■■■■■■	■■■■■	■■■■					■
Over 04 TD Site 9 [11] (108) <15>	■■■■■■	■■■■	■■■■■	■■■■				■ 3-5	

Key: ■ <2%, ■■ 2-5%, ■■■ 5-10%, ■■■■ 10-20%, ■■■■■ 20-30%, ■■■■■■ 30-40%, ■■■■■■■ 40-50%, ■■■■■■■■ 50-60%, ■■■■■■■■■ 60-70%

Key to the preservation of organic material: 1 = fresh; 2 = yellow; 3 = red-brown; 4 = brown; 5 = black

Table 5.6. The average percentage of iron coatings of voids and grains, and of iron replacement of organic material identified through micromorphological analysis.

Over Sample Name	Coatings of Grains and Voids (%)	Replacement of Organic Matter (%)
Over 04 TD Site 9 [9] (96) <8> a	5	
Over 04 TD Site 9 [9] (96) <8> b	8	<2
Over 04 TD Site 9 [9] (98) <9>	31	<2
Over 04 TD Site 9 <12>	19	
Over 04 TD Site 9 [11] (107) <14>	10	<2
Over 04 TD Site 9 [11] (108) <15>	28	<2

Samples 8 and 9 are from the pit/posthole, with sample 8 containing two units, 8a and 8b. Unit 8a is an iron- and organic-rich silty clay loam with a channel microstructure and some silty clay coatings of grains. Small fragments of unburnt reddened bone (300-570µm) are present; the reddening is the result of iron bonding with the bone. In addition, articulated and non-articulated phytoliths are abundant including various shapes: rectangular, triangular, square, elongate, serrated and spiny. The presence of articulated phytoliths is the result of *in situ* decay of plant material either by humification or burning (Stoops 2003, 74). The predominant organic material present in 8a is amorphous punctuations and fine amorphous organic matter (table 5.6). In addition, up to 30% of fine charcoal (<100µm) and up to 20% of coarse charcoal (>100µm) is present in the groundmass. There is <2% celled organic material present in this unit with fresh to yellow preservation, which suggests that this material may be a recent intrusion.

Unit 8b is a wood ash-rich fabric with iron- and organic-rich silty clay loam and a channel microstructure. There are some silty clay coatings of grains suggesting illuviation of fine material. The ashy deposits have a mottled concentration suggesting that this wood ash is not *in situ* but has been disturbed and unevenly distributed through the fabric. There is some amorphous vivianite present, suggesting that reducing conditions have occurred within the feature, either through groundwater movement or lack of oxygen through the burning of surrounding sediments. In addition, articulated and non-articulated phytoliths are present with the articulated phytoliths suggesting the *in situ* decay of plant material. These phytoliths have various shapes, similar to the phytoliths present in 8a. Amorphous punctuations and fine amorphous organic matter are predominant in 8b along with fine (<100µm) and coarse (>100µm) charcoal.

Sample 9 was taken from the iron pan at the base of the pit/posthole. It is an iron- and organic-rich fine sandy loam with silty clay fine material and a channel to crumb microstructure but is largely masked by iron. There is some wood ash, along with articulated and non-articulated phytoliths of various shapes, as well as some amorphous vivianite in the upper part of the section. This suggests that *in situ* decay of plant material has taken place and that reducing conditions were present at one time. Amorphous organic punctuations and fine organic matter predominate with up to 30% fine (<100µm) and 20% coarse (>100µm) charcoal present throughout the fabric.

The micromorphological analysis of the samples taken from the pit/posthole suggests two phases of use: first as a posthole and second as a pit. The presence of ashy deposits in the primary fill, 8b, suggests that the pit was filled with hearth rake-out as there was no distinct *in situ* layer of wood ash but a more mottled distribution of wood ash throughout the fabric. The secondary fill, resembles the fabric from the buried A horizon from sample 12, and is most likely the result of natural erosion/deposition of this material into the pit. The iron pan at the base of the feature could be the remnant of the post from the initial use of the feature, which has decayed leaving an iron imprint in the fabric. However, the presence of vivianite in the secondary fill of the pit suggests that reducing-oxidising conditions have occurred, most likely as a result of the fluctuating groundwater table. Consequent to fluctuating iron-rich groundwater, it is possible that an iron pan has developed along the cut of the feature where a change in texture (and/or pore space) has occurred. Further, there is an increase down profile within the pit of iron-rich clay coatings, which suggests that post-depositional illuviation has occurred (table 5.6). In addition, the presence of iron replaced organic material in the secondary fill and in the iron pan suggests that repeated reducing-oxidising cycles have occurred *in situ* (table 5.6).

Sample 14 is from the upper part of the ditch fill and is an iron- and organic-rich fine sandy loam with silty clay fine material, a channel to crumb microstructure and illuvial silty clay coatings of grains and voids. Phytoliths are present throughout the fabric along with Ca-P crypto-crystalline infillings from the decomposition of bone (Brothwell and Pollard 2001, 171); although no bone was present. Amorphous punctuations and fine amorphous organic matter predominate, along with fine (<100µm) and coarse (>100µm) charcoal (table 5.5). Sample 15 is from the base of the ditch and is an iron- and organic-rich fine sandy loam with silty clay fine material and a channel to crumb microstructure, but is largely masked by iron. There are some illuvial silty clay coatings of grains and voids as well as Ca-P crypto-crystalline infillings and some phytoliths throughout the fabric.

The fill of the ditch is similar to the palaeosol (sample 12) and it is likely that this ditch filled from natural erosion/deposition of this material. The presence of the iron pan at the base of this feature is likely to have occurred from the fluctuating iron-rich groundwater present at Over (French 2004); the presence of iron replaced organic material in both samples taken from the ditch confirm that redox processes were occurring here (table 5.6). In addition, there is an increase in iron-rich clay coatings of grains and voids down profile within the ditch, suggesting post-depositional movement of the fine material (table 5.6).

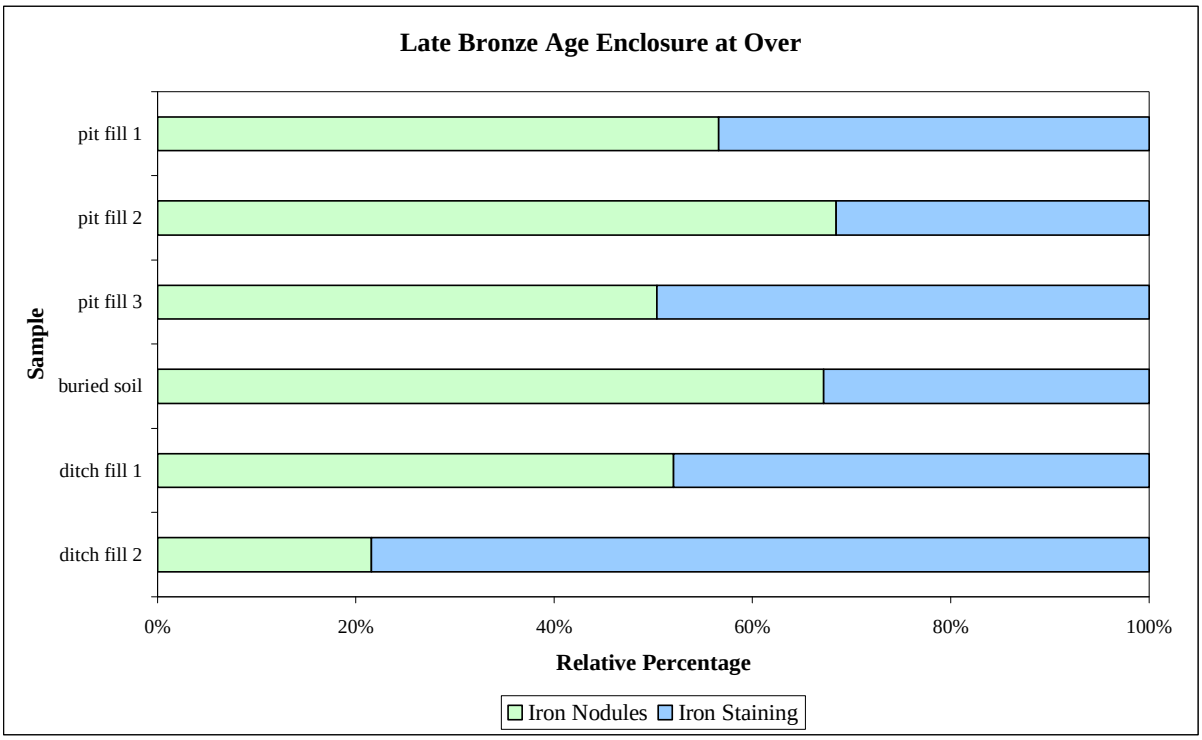


Figure 5.8. The relative percentage of iron nodules versus iron staining present in the samples collected from the Late Bronze Age enclosure at Over.

Finally, the presence of iron nodules and iron staining in the fabric provide information about the rate of oxidation in the soils. Iron nodules predominate in the samples from the primary and secondary pit fill, the buried soil and the upper fill of the ditch, whereas iron staining is predominant in the lower pit and ditch fills (figure 5.8). The predominance of iron staining in the lower pit and ditch fills is expected as these samples were taken from the iron pans at the base of the features. The predominance of iron nodules in the remaining samples most likely reflects the rapid oxidation of the sediments from the dramatic lowering of the groundwater table ahead of gravel extraction in the vicinity of the site. As discussed in the previous chapter, the rapid lowering of the groundwater table resulted in the leaching out of the finer material in the soil fabric, including much of the organic material, from the natural soil profile. Although there is evidence of organic decomposition (phytoliths, dominance of amorphous organic matter) in the archaeological sediments, which is the result of oxidation, they have retained much of their fine and organic material. This is most likely due to the presence of the iron pans, which have protected the sediments against leaching processes, and the capping of the site by alluvial overburden has prevented the erosion and mass movement of the finer material from the sediments.

5.3 IRON AGE RINGWORK AT WANDLEBURY

The Wandlebury Iron Age ringwork is situated approximately 6.5km southeast of Cambridge (TL 4940 5343) towards the northern end of the Gog Magog Hills, overlooking the Cam valley and Cambridgeshire fens (French *et al.* 2005b, 15). There is a mixed geology/soil type present at Wandlebury, which includes a typical rendzina on a chalk substrate and a calcareous brown earth on a remnant of glacial head material (*ibid*, 48). The ringwork encloses about 6.25ha and is situated on a natural hillock, at approximately 77m OD (*ibid*, 15). The site was excavated from 1994-1997 as a training exercise by the Department of Archaeology and the Cambridge Archaeological Unit (CAU), University of Cambridge (*ibid*). In addition to reassessing previous excavations carried out in 1955-1956, this excavation aimed to investigate the extent and preservation of archaeological features within the interior of the ringwork as well as outside the ringwork to the east and southeast, and to better understand the role of this monument in its surrounding landscape (*ibid*, 17).

There is evidence of settlement and land use at Wandlebury from the Late Bronze Age/very Early Iron Age through to the Romano-British period (*ibid*). The archaeological finds recovered during the 1994-1997 excavations at Wandlebury include pottery, flint, faunal and botanical remains, and human remains (*ibid*). The preservation of the organic material recovered at Wandlebury will be discussed here, as it is directly relevant to my research. For a full report of the excavations at Wandlebury please see French *et al.* (2005b).

The human skeletal remains were very well preserved making it possible to determine the age, sex and pathological history of the individual from childhood until death (*ibid*, 57). The state of preservation was not unusual given the calcareous burial environment. The preservation of the faunal remains varied by period, with good preservation in the Iron Age deposits and poor preservation in the Romano-British deposits (*ibid*, 46). This was most likely due to the rapid burial of the faunal remains in the pits during the Iron Age and the long term exposure of the faunal remains in the Romano-British period (*ibid*, 46). There was clear evidence of cut-marks and burning present in the faunal assemblage with a predominance of cut-marks present on the bones found within the ringwork, and a predominance of burnt bone present in the assemblages from outside the ringwork (*ibid*, 47). Although faunal remains were preserved at Wandlebury, 64.5% of the assemblage remained unidentifiable (*ibid*, 43).

The macro-botanical remains recovered from pits both inside and outside the ringwork were charred, and the preservation of these remains was directly related to the degree of charring

(*ibid*, 49). Those plant remains which were not charred or mineralised, were most likely rapidly degraded post deposition and were absent in the botanical assemblage at Wandlebury (*ibid*, 56). The samples that were more poorly preserved had characteristics which result from severe charring, whereas the samples that were better preserved lacked such characteristics (*ibid*, 49). There was a general trend of better preservation of samples from the pits outside the ringwork than those from within the ringwork, and the author suggested that this was either due to burning or variations in post depositional oxidising conditions (*ibid*). Further, it was noted that the preservation of macro-botanical remains was very poor in the samples taken from the buried soil beneath the inner rampart (*ibid*, 50) (an issue which will be highlighted below in the results from the current study). This was most likely due to the exposure, trampling and mechanical disruption of the remains during the construction of the monument, along with drainage/soil conditions of the buried environment (*ibid*), with possibly some decalcification occurring in the contemporary Early Iron Age soil.

The samples used for my research were collected by French during the course of these excavations (*ibid*). The micromorphology samples have been analysed by French focusing on land use and soil development of the palaeosols prior to the construction of the ringwork (*ibid*, 48). The samples include three profiles: two from the buried soil beneath the counterscarp bank and one from the buried soil beneath the inner rampart (table 5.7 and figures 5.9 to 5.11).

Table 5.7. The soil micromorphology and bulk samples collected from the Iron Age ringwork at Wandlebury, along with their field description and context.

Micromorphology Sample*	Field Description and Context	Associated Bulk Sample
Wan 94 Pr 1/1	Test Pit 6 - buried soil beneath counterscarp bank	Wan 94
Wan 94 Pr 1/2	Test Pit 6 - buried soil beneath counterscarp bank	Wan 94
Wan 94 Pr 1/3a	Test Pit 6 - buried soil beneath counterscarp bank	Wan 94
Wan 94 Pr 1/3b	Test Pit 6 - buried soil beneath counterscarp bank	Wan 94
Wan 95 Pr 2/1	Trench IX - also buried soil beneath counterscarp bank	Wan 95
Wan 96 Pr 10/1	Trench 40 - buried soil beneath inner rampart	Wan 96
Wan 96 Pr 10/2a	Trench 40 - buried soil beneath inner rampart	Wan 96
Wan 96 Pr 10/2b	Trench 40 - buried soil beneath inner rampart	Wan 96

* a and b signify separate units identified by soil micromorphology in the same sample

The palaeosol from beneath the counterscarp bank in test pit 6 included an organic A horizon, evident from the similarity of the profile to the topsoil and the presence of amorphous organic matter throughout the groundmass, as well as a distinctly different lower horizon (*ibid*). This lower horizon was predominantly illuvial silty clay with irregular aggregates of fine calcareous sand and was likely the result of the underlying geology of mixed glacial head/chalk subsoil (*ibid*). The concentration of the illuvial silty clay in the lower horizon and its absence in the A horizon suggested "considerable within-soil mass movement of fines down-profile", which was "caused by slaking of fines from an exposed topsoil associated with rainsplash erosion" (*ibid*, 48). This evidence, along with the mixing of fine calcareous sand with the predominantly clay loam horizon and its poor structural development, suggested that arable land use had occurred at Wandlebury (*ibid*, 48). Contrary to the palaeosol profile in test pit 6, the palaeosol beneath the counterscarp bank from trench IX was indicative of a rendzina soil, which developed directly on the chalk substrate (*ibid*). Along with differences in geology, the two buried soil profiles varied with the brown earth being de-turfed prior to, and/or in association with, the construction of the counterscarp bank, while the rendzina profile was not de-turfed but was buried by bank construction (*ibid*).

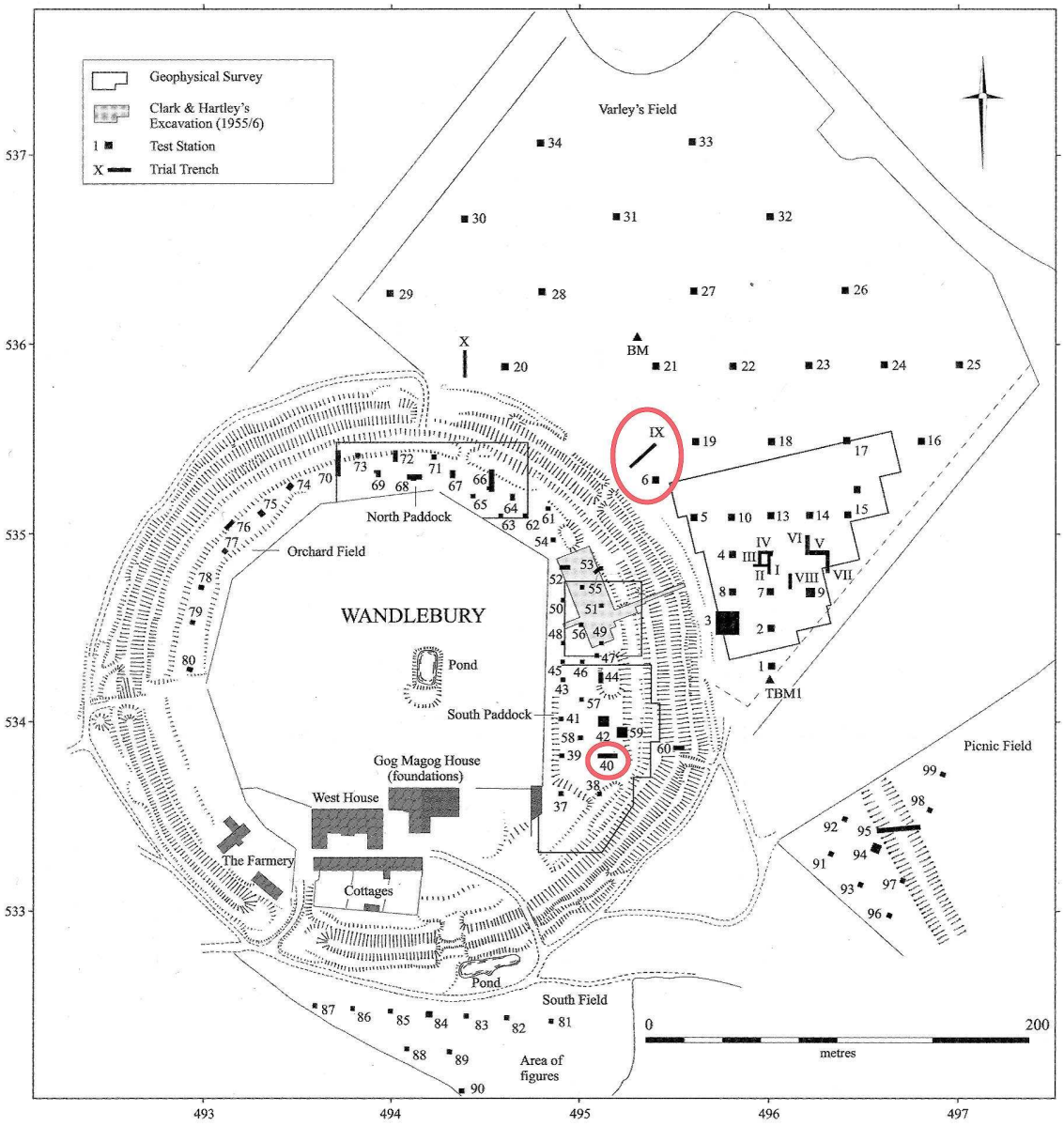


Figure 5.9. Location plan of the excavations and survey carried out in 1994-1997, adapted from French (Figure 4, 2005b, 21). The red circles indicate the trenches and test pit from which the samples were collected.

The buried soil beneath the inner rampart from trench 40 comprised two main horizons: the upper, a thick, dark brown, silt loam turf line, and the lower, a mix of chalk rubble fragments and thick, brown, silt loam (*ibid*). In addition, the upper horizon was dominated by amorphous iron and organic impregnation of the fine fabric, with small amounts (<10%) of pale brown calcitic sand (*ibid*). The palaeosol profile beneath the inner rampart was typical of a thin rendzina on a chalk substrate and although there was evidence of disturbance (calcitic aggregates), the turf line remained *in situ*, and therefore, was not de-turfed prior to the construction of the rampart (*ibid*). The disturbance that was evident was most likely the result



Figure 5.10. The buried soil beneath the counterscarp bank (photo: C.A.I. French).



Figure 5.11. Buried soil beneath the inner rampart (photo: C.A.I. French).

of mechanical mixing from human activities that took place within the ringwork earlier in the Iron Age (*ibid*).

The samples listed in table 5.7 were analysed with regard to iron oxide deposition and the preservation of organic material for comparison with the Wandlebury CDB site. The micromorphology samples were analysed using the same categories used for the CDB, as outlined in chapter three, and the bulk samples have been analysed using the same bulk analyses suite as the CDB samples. The results of these analyses with specific reference to iron oxide deposition and the presence of organic matter are presented in the sections below.

5.3.1 Bulk Analyses Data

The bulk samples from Wandlebury were collected from feature fills under the counterscarp bank (Wan 94 and Wan 95) and from the buried soil beneath the inner rampart (Wan 96). Sample Wan 94 is the tertiary fill of F15, which has been identified as a grain storage pit, and sample Wan 95 is the primary fill of F126 and has been identified as storage for bulk grain (French *et al.* 2005b, 28). The samples were run through a suite of bulk analyses, including ICP-AES for total Fe and Mn, LOI for %Water and %OM, PSD for %Clay, MS, pH, EC, redox and moisture content, the results of which are presented in table 5.8 below. $\%CaCO_3$ from LOI is also included in table 5.8 below. There are no VWC readings for this site as the opportunity was not available at the time of sample collection.

The bulk analyses results for the samples taken from beneath the counterscarp bank are distinctly different from the sample taken from beneath the inner rampart. There is significantly more Fe in Wan 96 than Wan 94 and Wan 95; however, given the evidence of burning occurring in the pits (Wan 94 and Wan 95), an increase in Fe is expected in these samples when compared to the buried soil beneath the inner rampart. Ash and charred plant remains were noted in the field and the high proportions of $CaCO_3$ and OM present in the samples confirm this observation (*ibid*, 28; table 5.8). Such unusual patterns of iron concentration are puzzling as those variables that are influenced by Fe quantities, such as MS and pH, and those that influence Fe quantities, such as OM and the clay-sized fraction of the sediment, are in direct opposition to Fe. Where Fe is relatively low, these other variables are high and vice versa. The samples from beneath the counterscarp bank, when compared to the sample beneath the inner rampart, are low in Fe but are high in Mn, OM, clay-sized

Table 5.8. Results for the bulk analyses carried out on the bulk samples collected from the Iron Age ringwork at Wandlebury; MC = moisture content.

Sample	Context	Fe (ppm)	Mn (ppm)	%Water (LOI)	%OM (LOI)	%$CaCO_3$ (LOI)	%Clay (PSD)	MS (x10^{-8} (m^3/kg))	pH	EC	Redox	MC (%)
Wan94	Feature fill - counterscarp bank	18100	693	2.11	6.42	41.53	14.78	17.52	8.20	169.33	135.33	2.14
Wan95	Feature fill - counterscarp bank	16000	603	1.84	3.51	55.27	12.49	32.10	8.48	100.67	130.67	2.06
Wan96	Buried soil - inner rampart	28200	144	1.39	2.61	0.71	8.55	1.56	7.64	52.67	145.67	1.45

Table 5.9. Results from ICP-AES for the plant nutrients present in the samples collected from the Iron Age ringwork at Wandlebury.

Wandlebury	Plant Macro-Nutrients							Plant Micro-Nutrients						
Sample Name	Al (ppm)	Ca (ppm)	Fe (ppm)	K (ppm)	Mg (ppm)	P (ppm)	S (ppm)	B (ppm)	Co (ppm)	Cu (ppm)	Mn (ppm)	Mo (ppm)	Na (ppm)	Zn (ppm)
Wan 94	9700	184000	18100	800	1800	1840	<100	10	6	26	693	1	300	71
Wan 95	9600	214000	16000	1100	1800	1880	<100	<10	5	24	603	1	300	73
Wan 96	6100	4400	28200	500	500	710	100	<10	7	8	144	1	100	43

particles, moisture, $CaCO_3$ and EC. Although the redox readings are slightly lower in the counterscarp samples, the readings for all three samples are within the moderately reducing range (cf. Cronyn 1990, 21).

A possible explanation for the lower amounts of Fe present in the counterscarp samples, despite evidence of burning, is that the pits were filled in after the burning event, thereby having no effect on the natural levels of Fe present in the sediment. Likewise, the quantity of Mn present in the sediment from the counterscarp samples is within the natural range of the soil, as presented in the previous chapter. However, the MS readings are well above the natural range at Wandlebury and suggest that Fe is not playing a major role in these results. Alternatively, other magnetically susceptible minerals, such as copper and cobalt, which are found in organic material (table 5.9), are more likely to be the main contributors to the high MS results at Wandlebury.

The higher levels of Fe from the samples beneath the inner rampart could be the result of decomposing organic material from the buried turf line, releasing the available iron. However, the relatively low quantities of other plant nutrients (table 5.9), along with the low EC values, suggests that the palaeosol beneath the inner rampart has undergone significant leaching, as these readings fall below those presented in chapter four. This is further supported by the low MS readings, suggesting that the Fe present is not magnetic and that other magnetically susceptible minerals in the soil are present in low quantities. The predominance of Fe present in the palaeosol suggests that the Fe present at the time of leaching was in an oxidised form and was therefore immobile, as is evident from the micromorphological analysis, observed by French (2005, 48) and quantified in section 5.3.2 below.

5.3.2 Soil Micromorphology

The soil micromorphology samples, listed in table 5.6 above, were re-analysed focusing on iron oxide deposition and the presence and preservation condition of organic material, the results of which are summarised in tables 5.10 and 5.11, and figure 5.12 below. The analyses follow the same criteria used for the CDB sites and the full descriptions are in appendix F. Although French (2005, 48) noted two separate fabrics in sample 10/1, the proportion of the secondary fabric was less than 10% and was insufficient for inclusion in my analyses.

Table 5.10. Results for the organic material, identified through soil micromorphological analysis, based on the protocol used for the CDB.

Wandlebury Sample Name	Amorphous		Charcoal	Charcoal	Celled			Plectenchyma	Pollen
	Punctuations	Matter	< 100µm	> 100µm	Lignified	Parenchymatic	Phlobaphene	(Fungi)	
Wan 94 Pr 1/1	■■■■■■■	■■■■	■■■■	■	■ 3-5	■ 3-5		■ 3-5	■
Wan 94 Pr 1/2	■■■■■■■	■■■■	■■■■	■	■ 2	■ 3-5			■
Wan 94 Pr 1/3a	■■■■■■■	■■■■	■■■■	■					
Wan 94 Pr 1/3b	■■■■■■	■■■■	■■■■	■		■ 2-5	■ 3	■ 3-5	
Wan 95 Pr 2/1	■■■■■■	■■■■	■■■■	■	■ 2-3		■ 3	■ 3-5	
Wan 96 Pr 10/1	■■■■■■■	■■■■	■■■	■					■
Wan 96 Pr 10/2a	■■■■■■■	■■■■	■■■	■				■ 3-5	
Wan 96 Pr 10/2b	■■■■■■	■■■■	■■■						■

Key: ■ <2%, ■■ 2-5%, ■■■ 5-10%, ■■■■ 10-20%, ■■■■■ 20-30%, ■■■■■■ 30-40%, ■■■■■■■ 40-50%, ■■■■■■■■ 50-60%, ■■■■■■■■■ 60-70%

Key to the preservation of organic material: 1 = fresh; 2 = yellow; 3 = red-brown; 4 = brown; 5 = black

Table 5.11. The average percentage of iron coatings of voids and grains, and of iron replacement of organic material identified through micromorphological analysis.

Wandlebury Sample Name	Coatings of Grains and Voids (%)	Replacement of Organic Matter (%)
Wan 94 Pr 1/1	16	<2
Wan 94 Pr 1/2	20	<2
Wan 94 Pr 1/3a	7	
Wan 94 Pr 1/3b	7	<2
Wan 95 Pr 2/1	14	<2
Wan 96 Pr 10/1	15	
Wan 96 Pr 10/2a	8	
Wan 96 Pr 10/2b	12	<2

The majority of the organic material present in the buried soils from beneath the counterscarp bank is in the form of amorphous punctuations (<1µm) and fine amorphous organic matter (>1µm) (table 5.10). There is some celled organic material present with varied preservation states, ranging from slightly decomposed (2-3) to very decomposed (4-5). There is also a significant amount of charcoal present, both less than and greater than 100µm. Overall, the buried soil from beneath the counterscarp bank has better preservation of organic material than the buried soil from beneath the inner rampart (table 5.10).

Similar to the palaeosol from beneath the counterscarp bank, the palaeosol from beneath the inner rampart is dominated by amorphous organic punctuations and fine amorphous organic matter. Unlike the counterscarp palaeosol, there is very little celled material present in the inner rampart palaeosol, and the organic material that is present is in poor condition. This supports the results from the bulk analyses, as well as evidence from the macro-botanical investigations (cf. French *et al.* 2005b, 50).

Iron coatings of grains and voids, iron replacement of organic material, iron nodules and iron staining are present in the sediments from the Iron Age site at Wandlebury (table 5.11 and figure 5.12). Iron pans are not present at this site. Iron coatings occur where clay impregnated with iron oxide moves down the soil profile through the process of illuviation. Iron coatings are present in the palaeosols from beneath the counterscarp bank and range from 7% to 20%, with higher concentrations of coatings in the upper part of the soil profile (table 5.11). It is possible that iron released during the decomposition of organic material in the A horizon has bonded with the clay particles, which have then illuviated down profile. The illuvial silty clay present in the lower horizons (French *et al.* 2005b, 48) and the lower percentage of iron coatings in sample 1/3, suggest that the clay in this horizon is more likely to be related to the underlying geology, or that the iron impregnation of the coatings occurred as post-depositional impregnation of translocated silty clay (*ibid*, 48). The palaeosol from beneath the inner rampart contains between 8% and 15% iron coatings of grains and voids (table 5.11) with the lowest frequency in the lower A horizon. Similar to the buried soil beneath the counterscarp bank, the clay coatings present are likely to have been impregnated with iron released from the decomposing organic material and then illuviated down profile, with the lower A horizon slightly more leached of iron coatings than the upper Ah and B/C horizons.

The replacement of organic material by iron oxide is present in the palaeosols from beneath the counterscarp bank and from beneath the inner rampart (table 5.11). This process occurs

from repeated wetting and drying cycles (redox) and suggests that reducing-oxidising conditions have been in play in these soils. However, the low frequency (<2%) of this iron replacement suggests that this process was not dominant in the buried soil environment.

As discussed in the previous chapters, iron staining and iron nodules provide valuable information about the oxidising conditions present in the soil environment. Iron nodules predominate in rapid oxidising conditions and iron staining predominates in slow oxidising conditions. The buried soil profile from beneath the counterscarp bank is dominated by iron nodules, suggesting rapid oxidation of the soils (figure 5.12). This may be the result of past arable use, the mechanical mixing of the soil, which occurred during the construction of the bank, and/or the bioturbation evident in the profile (*ibid*, 48).

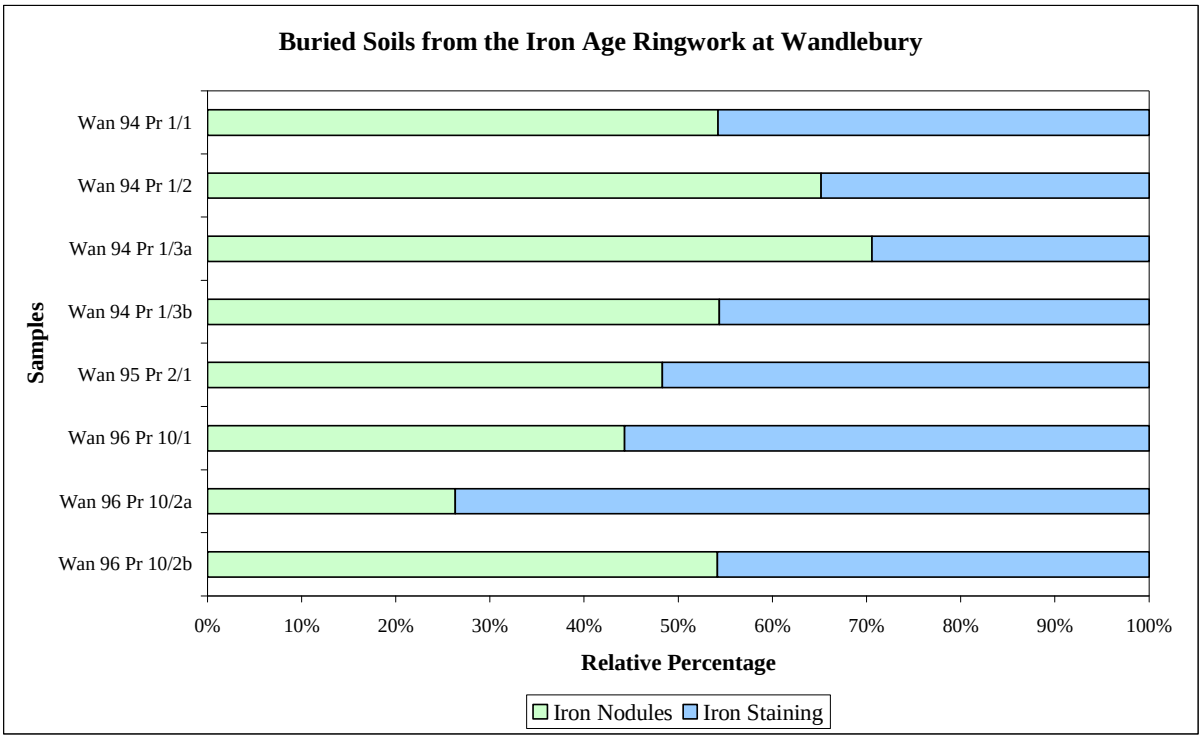


Figure 5.12. The relative percentage of iron nodules versus iron staining present in the samples collected from the Iron Age ringwork at Wandlebury.

The palaeosol beneath the inner rampart is dominated by iron staining in the Ah and lower A horizons and dominated by iron nodules in the B/C horizon (figure 5.12). This supports the description given by French, who noted a fabric dominated by amorphous iron impregnation of the fine fabric in the upper horizons, over a mixture of sandy loam and chalk (*ibid*, 48). Further, the decomposition of the organic material from the *in situ* turf line would have released ferrous iron, and the compaction from the inner rampart would have limited the ability of the iron to oxidise quickly, causing staining of the groundmass to predominate. The

increase in nodules over staining in the B/C horizon could be due to a lack of available ferrous iron in this horizon after sealing of the profile by the construction of the inner rampart. It is possible that the deposition of iron in this horizon represents the oxidising conditions prior to the rampart construction.

5.4 ROMANO-BRITISH SITE AT MARCHAM-FRILFORD

The Romano-British site at Marcham-Frilford (Oxfordshire) includes a large circular construction located in a natural hollow identified as an arena, a straight 'palaeochannel' that runs from the arena down towards the River Ock, and the Ock palaeochannel that runs east-west across Trendles field in which the site is situated (Hingley 1985; Lewis 2004a). During the 2004 season, questions regarding the hydrological nature of the palaeochannels and use of the arena were the focus of the excavation. At the south end of the arena, looking towards the River Ock, is a rectangular stone-built structure called the 'royal box' and it was suggested by Lewis that both the arena and the 'royal box' are "major works of hydrological engineering" (2004a, 3). During excavation in 2003 and 2004, a drain with stone capping was uncovered within a large ditch that runs from the 'royal box' down towards the river: the straight 'palaeochannel' (*ibid*). Above the drain is a complicated series of ditch fills with iron panning (trench 9), from which three micromorphological samples and three bulk samples for bulk analyses were collected (*ibid*; table 5.12, figures 5.13 and 5.14). During the 2004 season it was noted that the deposits from the Ock palaeochannel were almost wholly archaeological in nature and that this natural palaeochannel was advantageously altered by the Romans. Three micromorphological and four bulk samples for bulk analyses were collected from this palaeochannel (trench 21; table 5.12, figures 5.13 and 5.15).

The buried soil profile from trench 9 was sampled by Lewis in 2003 and described as a thin brown calcareous soil over Jurassic limestone, and was most likely grassland presumably used for pastoral purposes (Lewis 2003, 5). The post-abandonment deposits are described as a groundwater gley soil overlain by a 20-40cm deep colluvial deposit, most likely the result of downslope movement "from the north under the influence of historic ploughing" (*ibid*, 6). The site has a high groundwater table that fluctuates seasonally, identified by the iron mottled B horizon, which is within the zone of alternating groundwater levels. Below this zone are grey saturated sands and gravels that are permanently below the groundwater table (*ibid*).

Table 5.12. The soil micromorphology and bulk samples collected from the Romano-British site at Marcham-Frilford, along with their field description and context.

Micromorphology Sample*	Field Description and Context	Associated Bulk Sample
MF04 <9.29> a	orange/brown sand (9245) and part of a turve - just below (9254)	MF04 <9.30>
MF04 <9.29> b	orange/brown sand (9245) and part of a turve - just below (9254)	MF04 <9.30>
MF04 <9.31> a	base of ditch - black (organic) layer (9245)	MF04 <9.32>
MF04 <9.31> b	base of ditch - orange brown sandy layer (9245)	MF04 <9.32>
MF04 <9.33> a	below (9255) and above (9256) - across Fe/Mn pan - (part of a turve) above Fe pan	MF04 <9.34>
MF04 <9.33> b	below (9255) and above (9256) - across Fe/Mn pan - (part of a turve) Fe pan	MF04 <9.34>
MF04 <9.33> c	below (9255) and above (9256) - across Fe/Mn pan - (part of a turve) below Fe pan	MF04 <9.34>
MF04 <21.5>	across (21004) and (21011) - Fe mottle and dark grey silty to loamy clay, respectively	MF04 <21.1>
MF04 <21.6>	from (21011) - dark grey silty to loamy clay	MF04 <21.2>
MF04 <21.7> a	across (21015) and (21016) - white fine sandy clay (21015) (between (21016) and (21011))	MF04 <21.3>
MF04 <21.7> b	across (21015) and (21016) - dark grey silty organic-rich clay (21016) below 21015	MF04 <21.4>

* a, b and c signify separate units identified by soil micromorphology in the same sample

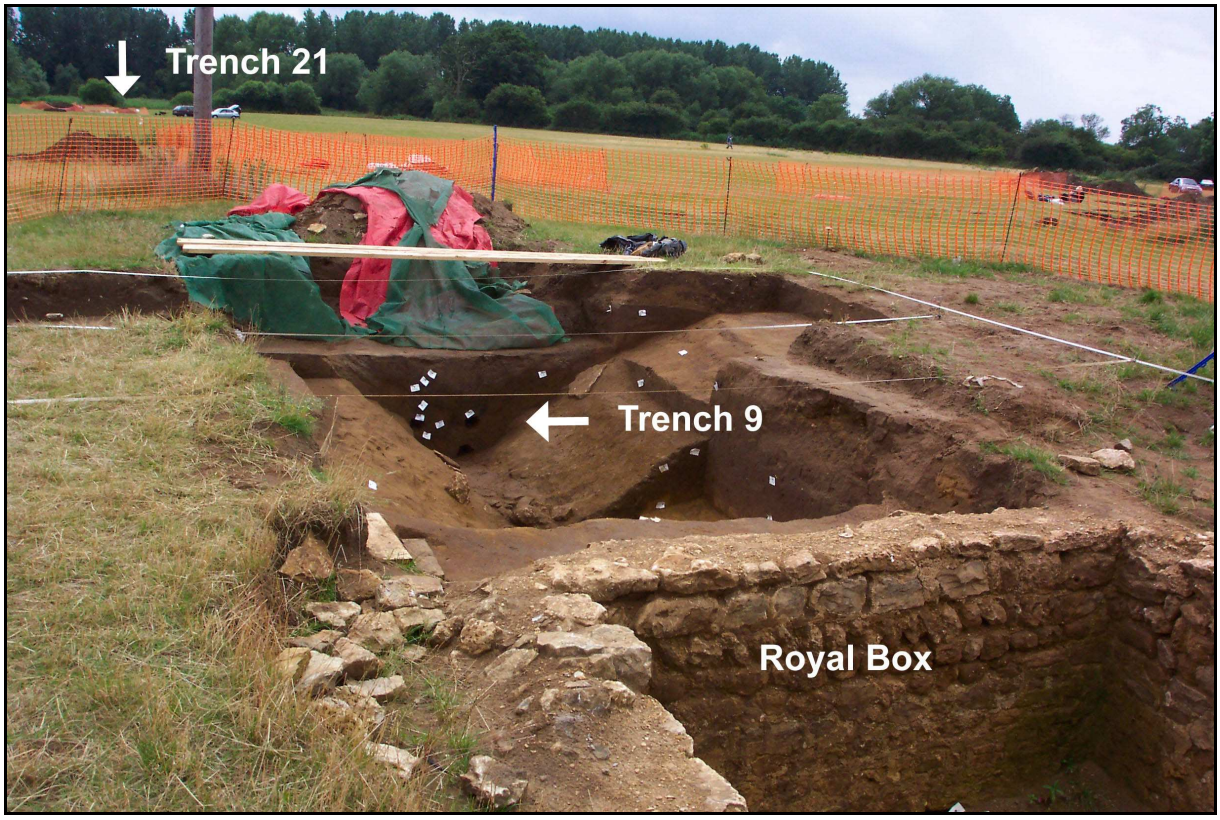


Figure 5.13. This photograph of the site at Marcham-Frilford shows the ditch (straight 'palaeochannel') and the 'royal box' (trench 9) in the foreground, with the Ock palaeochannel (trench 21) in the background. The River Ock is demarcated by the tree-line in the background.

The samples from Trenches 9 and 21 were collected to investigate the presence of iron oxide deposition in relation to oxidation. The high fluctuating groundwater table present at the site, and the clay-rich nature of the sediments, provide an ideal context in which to examine the effects of the hydrological environment and oxidising conditions on the preservation of archaeological organic remains.

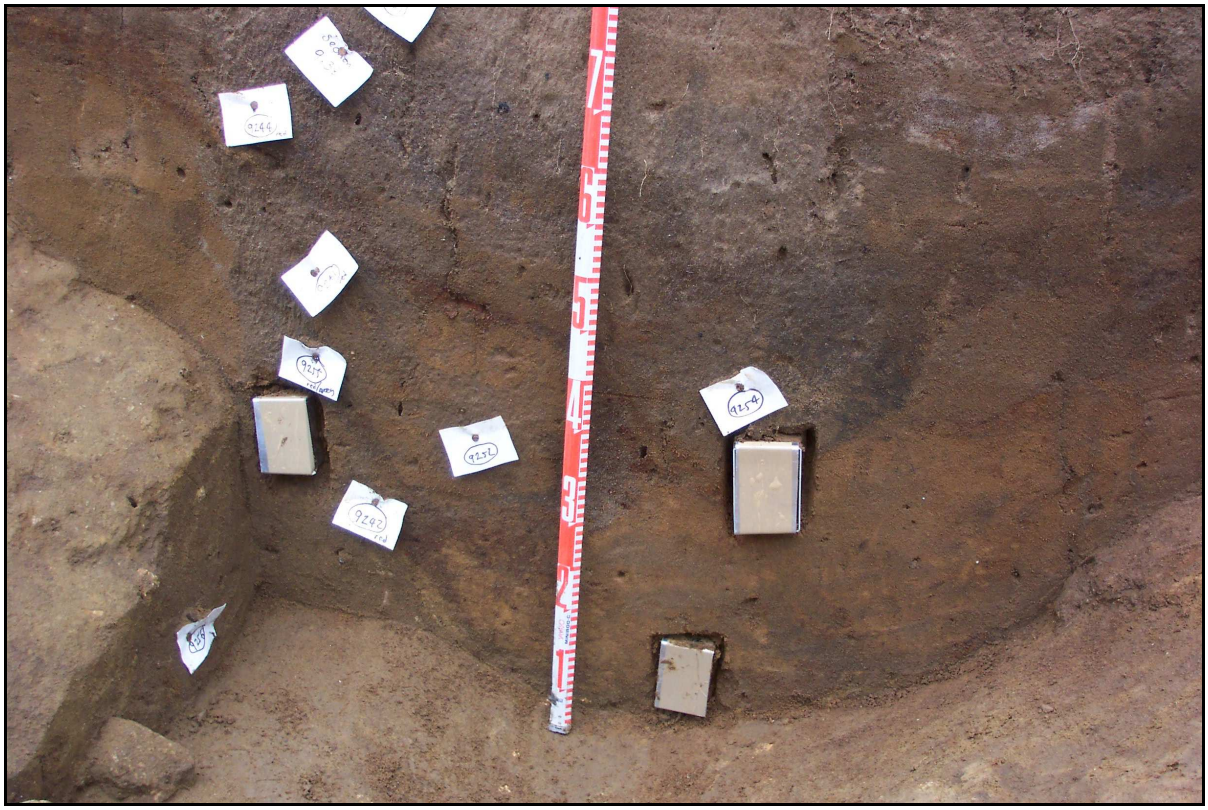


Figure 5.14. The location of the samples taken from trench 9, the 'palaeochannel' that leads from the arena and the 'royal box' towards the River Ock.

The samples collected from trench 9 were taken from the upper fill of the ditch where iron panning was present: one sample was taken across this iron pan, the second from a dark, possibly organic-rich deposit at the base of the section, and the third from one of the turves used to construct the feature (figure 5.14). Although the fluctuating groundwater table was attributed to the mottling present in the soils/sediments described by Lewis (*ibid*), the iron pan present in the upper fill of the ditch in trench 9 is more likely the result of decomposing organic material and compaction related to the backfilling of the ditch with turves.



Figure 5.15. This photograph depicts the location of the samples taken from the sediments in the Ock palaeochannel (trench 21).

The samples from trench 21 were taken from the fills from the Ock palaeochannel: one from the iron mottled layer, one from the grey sediment beneath the mottled layer, and one sample taken across a thin white layer and dark grey organic-rich layer towards the base of the excavated trench (figure 5.15). These samples were collected for their close vicinity to the groundwater table and the presence of iron-rich sediments, most likely from the effects of oxidising conditions influenced by the fluctuating groundwater table.

5.4.1 Bulk Analyses Data

A suite of bulk analyses were carried out on the bulk samples collected from the Romano-British site at Marcham-Frilford, which included ICP-AES for total Fe and Mn, MS, LOI for

%Water and %OM, PSD for %Clay, pH, EC and Redox (table 5.13). In addition, moisture content (%) and in-field moisture readings (VWC) were recorded (table 5.13).

The bulk analyses results for the samples taken from trench 9 indicate high levels of iron and manganese, as well as high magnetic susceptibility readings (table 5.13), which is expected given the panning present in the samples. This would indicate that the iron and manganese present in the sediment at Marcham-Frilford is largely responsible for the MS readings, as opposed to other minerals, which are released during organic decomposition (table 5.14). In addition, there is some organic material present, although the micromorphological analyses indicate significant iron replacement of organic material (see below). The redox results indicate that the sediments are moderately reducing and the EC readings show that the available soluble salts are low, perhaps indicating some form of leaching of soluble salts from the sediments. Alternatively, the low EC readings are representative of the hydrological environment in trench 9, where rainwater generally has lower conductivity levels than groundwater (Caple and Dungworth 1997), i.e. the groundwater is not affecting the oxidation processes of the sediments in trench 9. The sample taken from the base of the ditch has higher OM, moisture and clay content, which indicates that there is some movement of fine material downwards and that this fine material is most likely retaining the moisture available. This is confirmed by the micromorphology analyses, which will be discussed further below.

The bulk analyses results for the samples taken from trench 21, in contrast, have average to low amounts of iron and manganese, with the exception of MF 21.1, which is the iron mottled sediment. Again, the MS readings reflect the quantities of iron and manganese, suggesting that these elements are largely responsible for the readings, and that magnetic forms of iron and manganese are present. There is also an increase in OM, clay, EC and moisture towards the lower sediments, suggesting a movement of fines downwards, and indicating the presence of the high groundwater table. The lower amount of OM in the calcitic layer is confirmed below by the micromorphological analyses. The redox readings indicate that the sediments are moderately reducing and are, generally, more reducing values than in trench 9. The discrepancies between moisture content and VWC from the sediments in trench 21 are most likely due to the clay-rich nature of the sediments and their ability to hold pockets of moisture. As moisture content is measured from loose sediment in the laboratory, these pockets are no longer available, giving a lower estimation of the moisture within the sediments.

Table 5.13. Results for the bulk analyses carried out on the bulk samples collected from the Romano-British site at Marcham-Frilford; MC = moisture content.

Sample	Context	Fe (ppm)	Mn (ppm)	%Water (LOI)	%OM (LOI)	%Clay (PSD)	MS (x10 $^{-8}$ (m^3/kg))	pH	EC	Redox	MC (%)	VWC (%)
MF9.30	Turve from ditch	34500	815	1.78	2.91	12.81	3.48	8.11	51.00	136.33	19.47	19.00
MF9.32	Base of ditch	30500	861	2.04	3.11	19.11	1.97	7.89	51.00	145.67	23.83	35.33
MF9.34	Turve from ditch	24500	930	1.84	2.41	12.86	2.20	8.03	65.67	136.67	19.22	19.00
MF21.1	Fe mottle layer	58300	386	4.48	3.64	19.29	1.40	7.99	105.00	140.67	24.10	78.33
MF21.2	Silty clay layer	23200	158	3.87	3.66	16.62	0.69	8.16	113.00	134.67	17.82	97.33
MF21.3	Calcitic clay layer	12200	185	1.89	1.83	11.61	0.29	8.47	104.00	122.67	19.60	80.33
MF21.4	Organic rich clay layer	21000	305	4.39	6.52	18.35	0.72	8.09	205.67	132.00	23.50	103.67

Table 5.14. Results from ICP-AES for the plant nutrients present in the samples collected from the Romano-British site at Marcham-Frilford.

Marcham-Frilford	Plant Macro-Nutrients							Plant Micro-Nutrients						
Sample Name	Al (ppm)	Ca (ppm)	Fe (ppm)	K (ppm)	Mg (ppm)	P (ppm)	S (ppm)	B (ppm)	Co (ppm)	Cu (ppm)	Mn (ppm)	Mo (ppm)	Na (ppm)	Zn (ppm)
MF9.30	6100	5700	34500	600	700	870	200	<10	5	10	815	<1	100	42
MF9.32	6500	4300	30500	700	800	870	300	<10	7	9	861	1	100	36
MF9.34	7100	4100	24500	800	900	610	200	<10	6	8	930	<1	100	45
MF21.1	15000	12000	58300	2200	2200	3740	200	10	7	25	386	<1	200	91
MF21.2	14800	15200	23200	2200	2100	1340	200	10	6	23	158	<1	200	76
MF21.3	8400	48300	12200	1300	1400	620	200	<10	3	12	185	1	200	27
MF21.4	16200	52600	21000	2700	2500	1200	600	10	6	21	305	1	200	62

5.4.2 Soil Micromorphology

Soil micromorphological analyses were carried out on the samples collected from Marcham-Frilford following the same protocol used for the CDB sites. The results of these analyses are presented in appendix F, tables 5.15 and 5.16, and figure 5.16 below.

The samples collected from trench 9 were taken from two different turves with iron staining and panning present, and one from the base of the excavated ditch, which appeared to be more organic-rich than the remaining sediments. Sample 9.29 is consistent with material from an Ah horizon with a turf-line remnant of the buried soil described by Lewis (2003). The organic material present is largely decomposing, and iron replacement of organic material is present within the turf-line of the turf (tables 5.15 and 5.16). The turf-line is thick but, in comparison with the size of the turves (figure 5.14), is in proportion to the turf itself.

The second turf sample collected (9.33) has a distinct iron pan present and was originally thought to be lining separate construction phases of the ditch fill. Micromorphological analysis has shown that this material is similar to 9.29 and the iron pan is more likely to be the turf-line from one of the turves used to fill the ditch. There is clear orientation of the organic material present, along with significant iron replacement of the organic material, most likely the result of the decomposition of the organic material in the turf-line (table 5.16). A thick Ah horizon is associated with this turf-line, and represents a remnant of the buried soil described by Lewis (*ibid*).

The final sample, 9.31, is more organic-rich than the samples taken from the turves and this may be the result of eluviation from the sediments above, and subsequent illuvial deposition lower down the sediment sequence. The sediments from trench 9 are oxidised, with an abundance of manganese and iron and predominant decomposing organic material (tables 5.13 and 5.15). In addition, the iron coatings of voids present in all the sediments from trench 9 are most likely the result of decomposing organic material (table 5.16). Given the nature of these oxidised sediments, it is unlikely that the fluctuating groundwater table, the effects of which are clearly evident in other parts of the site, has had an effect on the sediments in trench 9, and is unlikely to have risen high enough to affect the iron oxide deposition in these sediments.

Table 5.15. Results for the organic material, identified through soil micromorphological analysis, based on the protocol used for the CDB.

Marcham-Frilford	Amorphous		Charcoal	Charcoal	Celled			Plectenchyma	Pollen
Sample Name	Punctuations	Matter	< 100µm	> 100µm	Lignified	Parenchymatic	Phlobaphene	(Fungi)	
MF04<9.29> a	■■■■■■■	■■■■	■■■	■				■ 3-5	
MF04<9.29> b	■■■■■■■	■■■	■■						
MF04<9.31> a	■■■■■	■■■■	■■■					■ 3-5	■
MF04<9.31> b	■■■■■■	■■■■	■■■			■ 3		■ 3-5	■
MF04<9.33> a	■■■■■■	■■■■	■■■					■ 3-5	■
MF04<9.33> b	■■■■■	■■■■	■■			■ 3-5		■ 3-5	■
MF04<9.33> c	■■■■■	■■■■	■■					■ 3-5	
MF04<21.5>	■■■■■■	■■■■■	■■■■	■■					
MF04<21.6>	■■■■■■	■■■■■	■■■■	■■					
MF04<21.7> a	■■■■■	■■■	■■■■	■					
MF04<21.7> b	■■■■■■■	■■■■■■	■■■■■	■	■ 3-5	■■■■ 3-5			

Key: ■ <2%, ■■ 2-5%, ■■■ 5-10%, ■■■■ 10-20%, ■■■■■ 20-30%, ■■■■■■ 30-40%, ■■■■■■■ 40-50%, ■■■■■■■■ 50-60%, ■■■■■■■■■ 60-70%

Key to the preservation of organic material: 1 = fresh; 2 = yellow; 3 = red-brown; 4 = brown; 5 = black

While the deposition of the turves in the ditch does not appear to be from natural processes, based on the size of the individual turves, there does not appear to be any particular design to the positioning of the turves in the ditch, which suggests that they were used to fill in the ditch haphazardly. This may have been an attempt to prevent further seepage of the groundwater table, or simply backfilled as part of the construction and/or maintenance of the drainage system leading down to the River Ock (see Lewis 2004).

Table 5.16. The average percentage of iron coatings of voids and grains, and of iron replacement of organic material identified through micromorphological analysis.

Marcham-Frilford Sample Name	Coatings of Grains and Voids (%)	Replacement of Organic Matter (%)
MF04<9.29> a	17	
MF04<9.29> b	20	<2
MF04<9.31> a	10	
MF04<9.31> b	7	
MF04<9.33> a	7	
MF04<9.33> b	6	10
MF04<9.33> c	8	
MF04<21.5>	13	<2
MF04<21.6>	9	<2
MF04<21.7> a	2	<2
MF04<21.7> b	1	5

The samples collected from trench 21 were taken down profile of the fill of the Ock palaeochannel on the west side of the trench. The first sample (21.5) was taken from the layer with distinct iron oxide mottling of grey fine sandy clay. The second (21.6) sample was taken from the dark grey loamy clay sediment below the mottled layer, and the third sample (21.7) was taken across a white clay layer, which appeared to be very distinct from the surrounding sediments, and the dark grey sandy clay layer below.

The micromorphological analyses of the samples from trench 21 have shown that the variation seen in the field between these layers is, in fact, the result of post-depositional processes rather than an intentional deposition of the different materials within the palaeochannel. The fabric from each of the samples is fine sandy clay with small micrite nodules and limestone fragments, and essentially consists of the same fabric throughout. The variations in colour, i.e. iron mottling and white sandy clay, are the result of groundwater movement and oxidation of the sediment. The iron oxide deposition evident in 21.5 (context

21004) is most likely the result of the natural fluctuations of the groundwater table and was, at one point, the fluctuation zone, resulting in the mottling observed in the field. The white sandy clay layer in 21.7 (context 21015) is impregnated with calcium carbonate and is most likely the result of the groundwater table stabilising at this point long enough for the precipitation of calcium carbonate from the alkaline groundwater to oxidise and impregnate the fabric. There are no distinctive boundaries for this layer, rather a gradual transition from a predominantly clay fabric to a predominantly calcitic fabric.

The samples from trench 21 have significantly more organic material than the samples from trench 9, as well as higher quantities of charcoal (table 5.15). The sample closest to the groundwater table (21.7b) also contains significant amounts of celled material compared to the samples higher up the profile, albeit in various decomposing stages (table 5.15). There is a distinct difference in the quantity and type of organic material present in the calcitic layer of 21.7a, which may be due to the masking of the fine sandy clay fabric by calcite, making it difficult to identify other characteristics present in the sediment (table 5.15). There is a decrease in iron coatings of grains and voids present in the fabric down profile (table 5.16) indicating that the oxidation of ferrous iron in the clay component of the sediment becomes less frequent. This suggests that although illuviation of silty clay is present throughout, iron oxidation of these silty clay coatings and/or the illuviation of iron-rich clay coatings, is not a dominant process in the lower sediments from trench 21. In addition, there is some iron replacement of organic material present in each of the samples, with slightly higher quantities in 21.7b, the sediment closest to the groundwater table (table 5.16). This is indicative of a fluctuating groundwater table in conjunction with decomposition of the organic material after exposure to oxidising conditions.

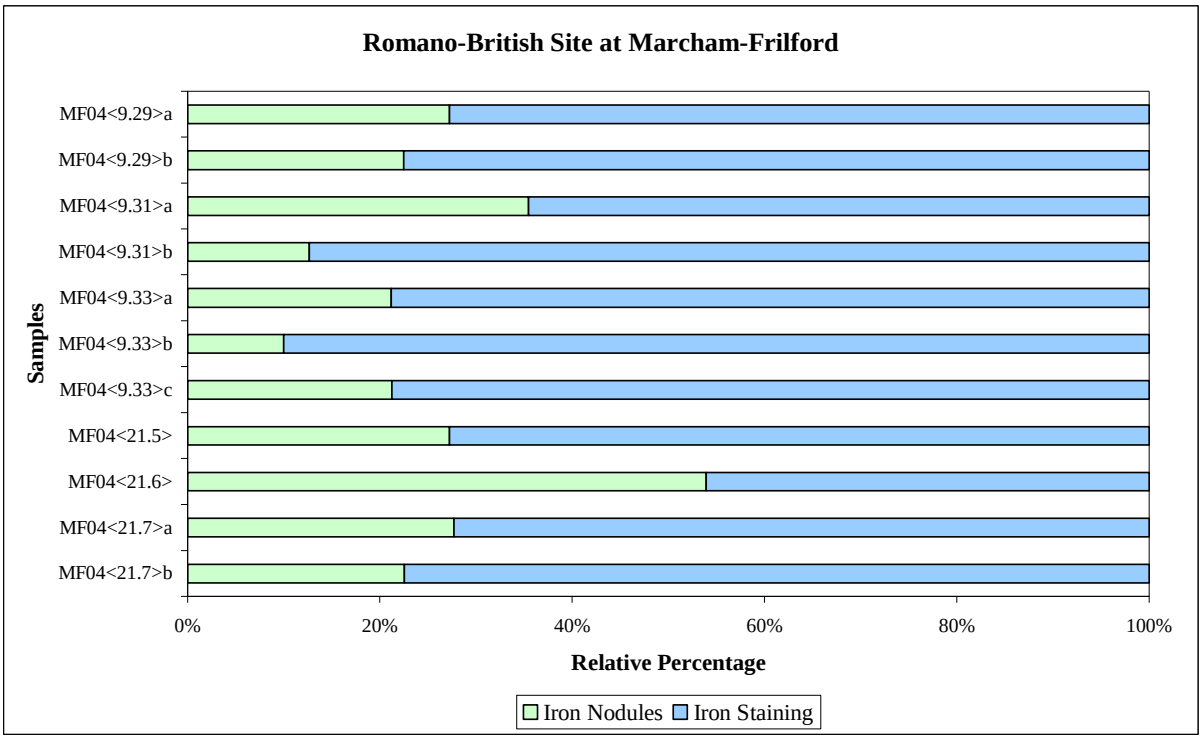


Figure 5.16. The relative percentage of iron nodules versus iron staining present in the samples collected from the Romano-British site at Marcham-Frilford.

Finally, iron staining and iron nodules were evident in the sediments from both trench 9 and trench 21; with a predominance of iron staining over iron nodules (figure 5.16). Given the naturally fluctuating groundwater table present at Marcham-Frilford, which is a process that introduces oxygen at a slow rate, the predominance of iron staining is expected as this type of iron oxide deposition is a direct result of the slow oxidation of the sediments. The preservation conditions at this site are quite good, particularly in trench 21 where bone, wood, charcoal, roman coins, pottery and metal have been recovered during excavation (Mike Langford, pers. comm.; Lewis 2003, 2004), suggesting a high, naturally fluctuating groundwater table is beneficial for the preservation of organic material in archaeological sites.

5.5 IRON AGE ENCLOSURES AT SUTTON COMMON

Sutton Common is situated approximately 40km south of York on "a narrow strip of peatland lying between the dipslope of the Magnesian limestone and silts and clays of pre-glacial Lake Humber" (Parker Pearson and Sydes 1997, 221; Van de Noort *et al.* 2001). Although there is evidence of occupation at Sutton Common from the Early Mesolithic to the medieval period, the focus of archaeological investigation has been on the two Iron Age enclosures situated on early Holocene sandy 'islands', between which is a peat and alluvium-filled palaeochannel (figure 5.17) (Chapman and Cheetham 2002; Parker Pearson and Sydes 1997; Van de Noort

et al. 2001). The enclosures are between 4.5m and 5.6m above sea level and prior to 1979, the site remained waterlogged with excavations in the 1930s recovering well preserved artefacts, such as a wooden wheel, and many stakes and posts (*ibid*). From about 1979-1980 arable agriculture, irrigation and water abstraction off-site caused the lowering of the groundwater table and subsequent decomposition of the organic archaeological artefacts, which had previously been preserved in a relatively undisturbed waterlogged environment (*ibid*).

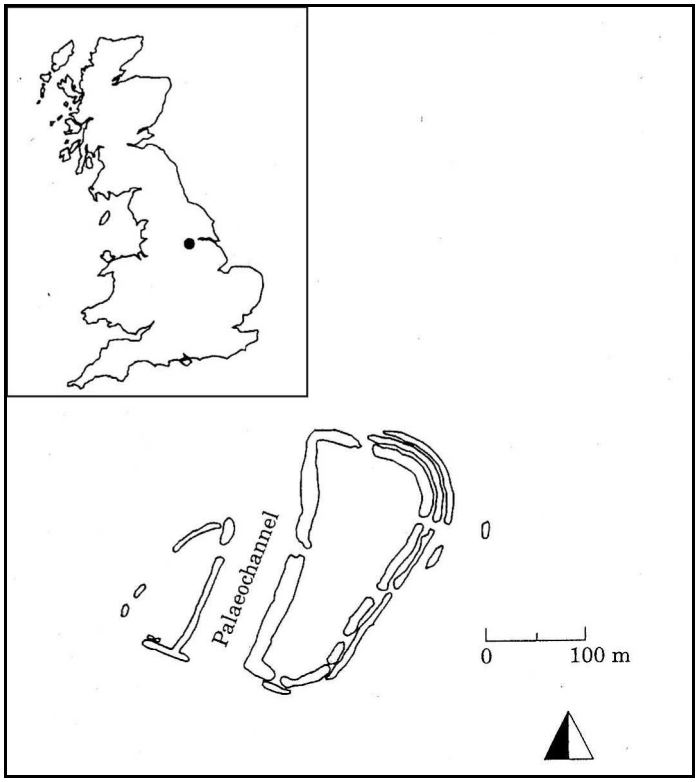


Figure 5.17. The location of Sutton Common in South Yorkshire, and the outlines of the banks of the two Iron Age enclosures (adapted from Chapman and Cheetham 2002, 281).

From 1987 to 1993, archaeological investigations were carried out at the site by Parker Pearson and Sydes (1997), who documented the preservation and desiccation of the site and the organic material contained within. The enclosures contained a variety of organic remains, including wood with identifiable tool marks, pollen, insects, waterlogged macrobotanical remains and charred plant remains (*ibid*). Since this report on Sutton Common, the site has undergone *in situ* monitoring to assess the effects of dewatering on the preservation of the archaeological organic remains (Chapman and Cheetham 2002; Van de Noort *et al.* 2001). The Sutton Common Project is a monitoring programme set up to assess the problems involved with *in situ* preservation of archaeological sites (*ibid*). It aims to preserve the organic archaeological and palaeoenvironmental records by developing a science-based approach to *in*

situ preservation (*ibid*). It integrates hydrological monitoring and predictive modelling of changes in the hydrological conditions of the burial environment, to better understand the complexity involved in conserving archaeological and palaeoenvironmental material data (*ibid*).

In 2003, Gianna Ayala and Matthew Canti (English Heritage) assessed the Iron Age enclosures at Sutton Common in the final year of excavation, and collected ten block samples for micromorphological analyses and eleven bulk samples, which were kindly passed on to me for this research project.[1] The bulk samples were used for a suite of bulk analyses and the micromorphological samples were analysed to assess the different types of iron oxide deposition, and how this relates to the effects of oxidation on the organic material present in the samples. The samples provided are from a modern soil sequence (figure 5.18), two posthole features (figures 5.20 and 5.21) and a buried soil profile (figure 5.19), which includes topsoil and subsoil material (table 5.17).

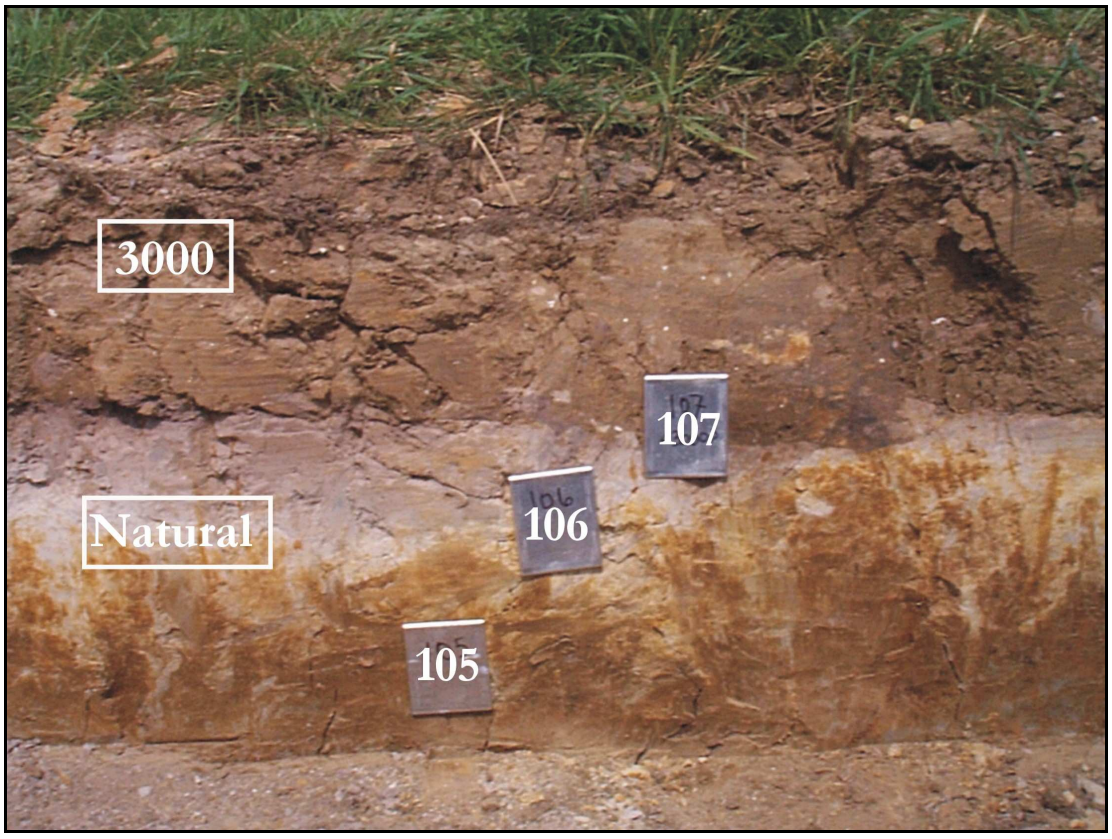


Figure 5.18. Location of the samples taken from the modern soil profile in trench 3 at Sutton Common (photo: Gianna Ayala).

[1] Ayala's (2003) report outlines the purpose and specific aims for their investigations and I refer the reader to this report for further information.

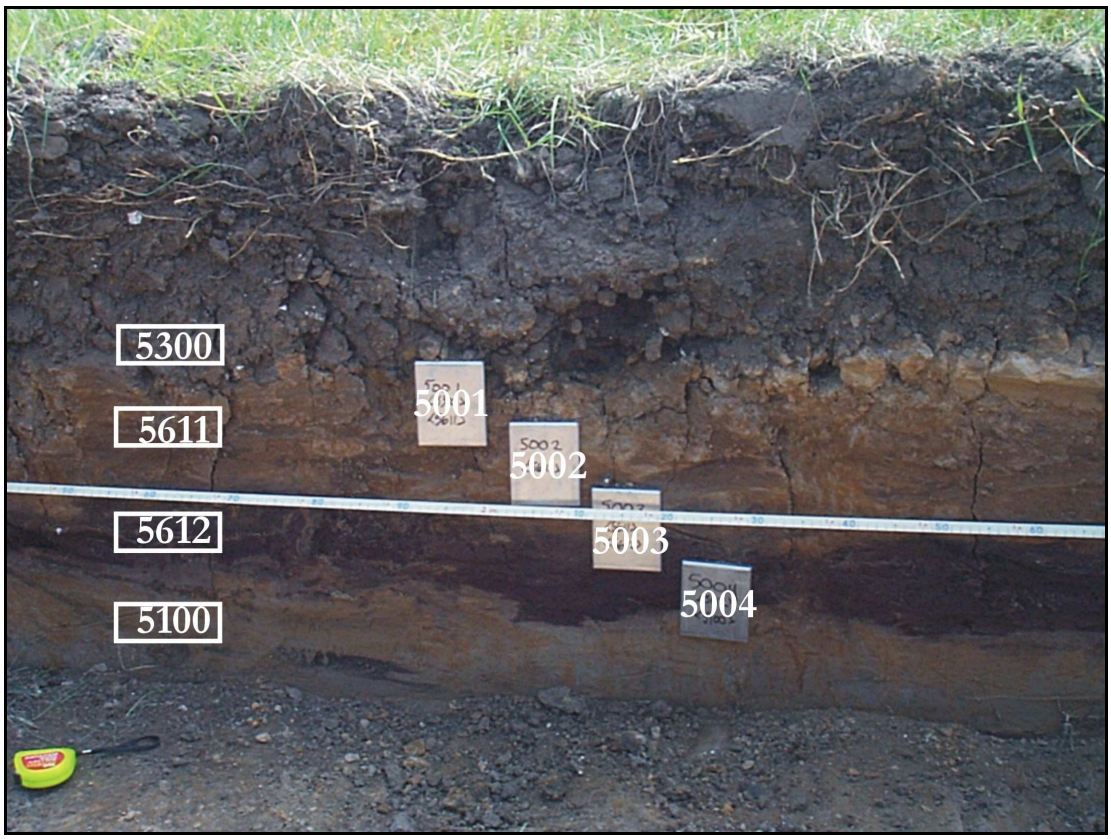


Figure 5.19. Location of samples taken from trench 5 including the Ap, subsoil, and buried soil horizons (photo: Gianna Ayala).

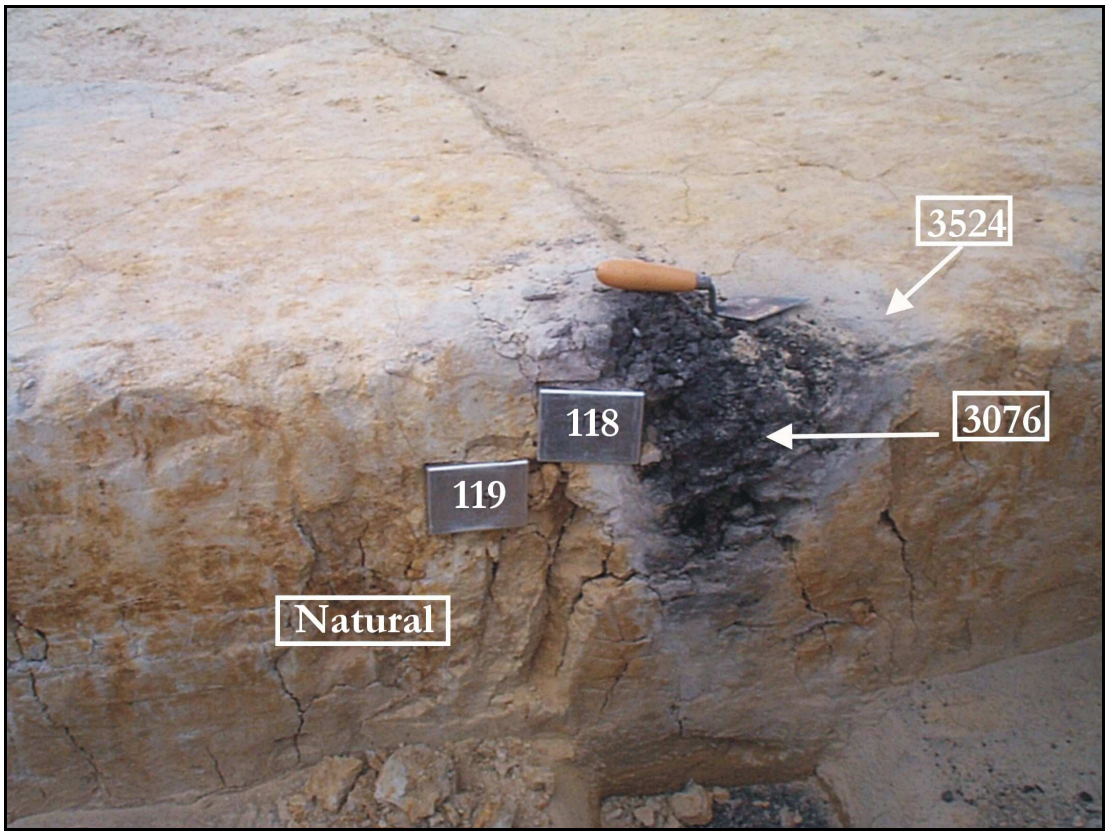


Figure 5.20. Location of samples 118 and 119 taken from the first posthole feature (photo: Gianna Ayala).



Figure 5.21. Location of sample 120 from the second posthole feature (photo: Gianna Ayala).

Table 5.17. The soil micromorphology and bulk samples collected from the Iron Age enclosures at Sutton Common, along with their field description and context.

Micromorphology Sample*	Field Description and Context	Associated Bulk Sample
SC2003 107a	Ap; greyish brown silty clay loam, with common fine $CaCO_3$ nodules and exhibiting discontinuous iron mottling	Trench 3 0-21
SC2003 107b	possible A/E horizon; light brownish grey silty clay loam	Trench 3 21-24
SC2003 106a	E horizon; white very fine sand with few discontinuous iron mottling	Trench 3 24-28
SC2003 106b	possible E/B horizon; pale yellow very fine sand with common orange streaks of iron mottling	Trench 3 28-40
SC2003 105	Bts horizon; light yellowish brown clay with streaks of organic material	Trench 3 40-53
SC2003 118a	sample taken radiating from 1st posthole - nearest to posthole - corner of posthole	Trench 3 F13 SE Corner <3189>
SC2003 118b	sample taken radiating from 1st posthole - nearest to posthole - sediment surrounding posthole	Trench 3 F13 SE Corner <3189>
SC2003 119a	sample taken radiating from 1st posthole - furtherest from posthole	Trench 3 F13 SE Corner <3189>
SC2003 119b	sample taken radiating from 1st posthole - furtherest from posthole	Trench 3 F13 SE Corner <3189>
SC2003 120a	sample taken radiating from 2nd posthole - including posthole, grey stuff and Fe mottling; black sediment from posthole	Trench 3 F13 SE Corner <3189>
SC2003 120b	sample taken radiating from 2nd posthole - including posthole, grey stuff and Fe mottling; grey sediment between posthole and orange-brown sediment	Trench 3 F13 SE Corner <3189>
SC2003 120c	sample taken radiating from 2nd posthole - including posthole, grey stuff and Fe mottling; orange-brown sediment surrounding posthole	Trench 3 F13 SE Corner <3189>
SC2003 5001	Ap; dark greyish brown, fine sandy silty clay loam with subangular blocky structure, common discontinuous iron mottling, frequent fine (1-2mm) $CaCO_3$	Trench 5 0-30
SC2003 5002	subsoil material; very fine sand, light grey with Fe mottling, continuous orange bands, rare charcoal (2-5mm) and organic material	Trench 5 31-52
SC2003 5003	buried A?; very dark greyish brown silty clay loam with common organic matter	Trench 5 52-60
SC2003 5004a	grey organic layer between buried A and C - transition between layers - possible Bh	Trench 5 52-60
SC2003 5004b	C horizon; light grey sandy clay loam with common discontinuous Fe mottling	Trench 5 60-

* a, b and c signify separate units identified by soil micromorphology in the same sample

Field observations in table 5.17 are from Ayala (2003) and describe the soil profile at Sutton Common as a podzolic brown soil with evident eluvial and illuvial horizons.

5.5.1 Bulk Analyses Data

The bulk samples collected by Ayala and Canti were used here for a suite of bulk analyses, including ICP-AES for total Fe and Mn, LOI for %Water and %OM, PSD for %Clay, MS, pH, EC and redox. The samples arrived after being air dried for several months so the moisture content (%) measured is not a reading of the soil moisture content at the site, but reflects the moisture content of the sediments after a period of air drying. In-field moisture readings were not taken at Sutton Common as access to the site was not possible. The results of the bulk analyses are presented in table 5.18 below.

Table 5.18. Results for the bulk analyses carried out on the bulk samples collected from the Iron Age enclosures at Sutton Common; MC = moisture content.

Sample	Context	Fe (ppm)	Mn (ppm)	%Water (LOI)	%OM (LOI)	%Clay (PSD)	MS (x10 $^{-8}$ (m^3/kg))	pH	EC	Redox	MC (%)
SC04 T3 0-21	Ap horizon	19500	340	2.22	5.64	6.28	0.57	8.06	112.00	177.33	2.22
SC04 T3 21-24	A/E horizon	6200	49	1.48	3.99	17.31	0.21	6.96	45.67	157.00	1.48
SC04 T3 24-28	E horizon	6800	57	0.95	1.73	5.87	0.11	7.59	41.00	176.67	0.95
SC04 T3 28-40	E/B horizon	22700	229	1.60	2.77	12.56	0.33	7.52	42.00	174.00	1.60
SC04 T3 40-53	Bts horizon	46300	907	2.79	4.09	18.27	0.51	7.48	95.00	174.33	2.79
SC04 T3 F13	Post hole	24900	362	2.02	4.14	17.46	0.43	3.03	3197.67	421.33	2.02
SC04 T5 0-30	Ap horizon	28800	703	2.88	7.54	15.91	1.67	7.61	161.33	57.33	2.88
SC04 T5 31-52	Subsoil material	40800	457	2.29	3.85	16.55	0.50	7.38	57.33	45.67	2.29
SC04 T5 52-60	Buried A horizon	5800	53	3.62	11.88	15.03	0.13	6.83	107.00	90.00	3.62
SC04 T5 60+	C horizon	10000	91	1.37	2.45	14.67	0.23	6.77	68.00	101.00	1.37

Table 5.19. Results from ICP-AES for the plant nutrients present in the samples collected from the site at Sutton Common.

Sutton Common	Plant Macro-Nutrients							Plant Micro-Nutrients						
Sample Name	Al (ppm)	Ca (ppm)	Fe (ppm)	K (ppm)	Mg (ppm)	P (ppm)	S (ppm)	B (ppm)	Co (ppm)	Cu (ppm)	Mn (ppm)	Mo (ppm)	Na (ppm)	Zn (ppm)
SC04 T3 0-21	10900	6300	19500	600	1300	210	500	<10	6	12	340	1	200	35
SC04 T3 21-24	8400	3300	6200	500	600	100	400	<10	2	10	49	<1	200	14
SC04 T3 24-28	6200	1400	6800	500	500	40	100	<10	2	2	57	1	200	12
SC04 T3 28-40	9700	1800	22700	800	1300	40	200	<10	7	10	229	1	200	43
SC04 T3 40-53	16600	3500	46300	1300	2000	60	200	<10	12	26	907	1	200	84
SC04 T3 F13	7300	1400	24900	1300	1600	240	15400	<10	7	15	362	1	200	40
SC04 T5 0-30	13900	8400	28800	800	2300	290	500	<10	7	16	703	1	200	57
SC04 T5 31-52	13600	3400	40800	1000	1900	130	400	<10	8	13	457	<1	200	68
SC04 T5 52-60	11400	7600	5800	600	1200	270	1700	<10	4	38	53	1	200	34
SC04 T5 60-	9600	1700	10000	800	1000	90	100	<10	5	8	91	1	200	65

The results from the bulk analyses carried out on the modern soil profile reflect the field descriptions taken by Ayala (2003), with clear eluvial and illuvial horizons. There is significant translocation of clay and organic material and leaching of soil nutrients from the E horizon and subsequent deposition, or illuviation, of this material in the lower Bts horizon (tables 5.18 and 5.19). Further, soil moisture, measured by both LOI (%Water) and moisture content, shows a decrease in the eluvial horizon and an increase in the illuvial horizon, suggesting that the presence of clay, soil nutrients and organic material is necessary for the soil to retain moisture.

The Ap and subsoil horizons within the buried soil profile have higher values of Fe and Mn than the buried A and C horizons. It is possible that arable activity in the Ap and subsoil horizons have increased the natural levels of these minerals in the soil, or that the soluble Fe and Mn present in the buried soils have been carried away with the lowering of the groundwater table, due to irrigation and water abstraction off-site. There are no significant differences in the amount of clay between each horizon; however, the variation in OM, %Water and EC show an increase in the Ap horizon, depletion in the subsoil, followed by an increase in the buried A horizon and subsequent depletion in the C horizon. The increase of these variables in the buried A horizon could be attributed to the significant decrease in the percentage of soil pore space for this horizon, as identified through soil micromorphology (from 25% in the subsoil to 15% in the buried A horizon). The compacted nature of the buried A horizon prevented the leaching of OM and soil nutrients from the soil, while the more aerated upper horizons and C horizon (20%) promoted the leaching of this material from the soil (tables 5.18 and 5.19).

The sample from the posthole has similar Fe, Mn, moisture, clay and OM levels to the Ap horizons of both soil profiles; however, pH, EC and redox differ significantly. The sediment from this feature is highly acidic (pH 3.03) with a dramatic increase in soluble salts (3197.67 µS), and redox potential reveals the posthole is an oxidising sediment (421.33 mV); however, the redox potential for the soil profiles indicates the sediments are moderately reducing to reducing, are circum-neutral to alkaline, and have relatively low EC values. Further, there is a significant increase in sulphur, which may be remnant of the *in situ* decomposition of wood within the posthole. Although there is no significant increase in %OM, the highly oxidising conditions in the sediment will have caused the total decomposition of any OM remaining in the sediment. In addition, the increase in sulphur, the high EC values, and increased acidity,

are most likely remnants of this same process of organic decay, as during decomposition, acids and plant nutrients are released into the surrounding soil/sediment.

Finally, the generally low MS readings for all the samples analysed, suggest that the Fe and Mn present in the soils and sediments at Sutton Common are not magnetic, and additionally negate any *in situ* burning as a cause for the highly oxidised sediment in the posthole. Rather, the oxidation in this feature is more likely the result of microbial activity during the breakdown of the organic material, in addition to the lowering of the groundwater at the site.

5.5.2 Soil Micromorphology

Soil micromorphological analyses were carried out on the samples collected from Sutton Common following the same protocol used for the CDB sites. The results of these analyses are presented in appendix F, tables 5.20 and 5.21, and figure 5.22 below.

The modern profile from trench 3 (samples 105 to 107) is indicative of a podzolic soil profile; however, the abrupt boundary between the Ap horizon and the A/E horizon indicates that some truncation has occurred. This possibility was suggested by Ayala (2003) and is most likely the result of the site being bulldozed in the 1980s. The Ap horizon is rich in organic material with amorphous and celled plant material present, along with fine and coarse charcoal (table 5.20). The A/E and E horizons exhibit lower quantities of organic material and charcoal with a slight increase in the lower E/B and Bts horizons (table 5.20). In addition, there is a similar pattern with iron coatings of grains and voids (table 5.21) with a dramatic decrease in the E horizon and increase in the Bts horizon. Iron replacement of organic material is present in small quantities in the Ap, E and E/B horizons. This suggests that the replacement of the organic material occurred prior to the eluviation of fine material from the E and E/B horizons. Further, the presence of iron replaced organic material indicates fluctuations in groundwater levels and repeated cycles of reducing and oxidising conditions taking place prior to the development of the current profile. The subsequent leaching of fine material from the upper horizons and illuviation in the lower profiles is most likely remnant of processes that occurred after the mechanical lowering of the local groundwater table through irrigation and water abstraction.

The upper horizons of trench 5 are indicative of modern Ap and B horizons with high quantities of organic material, including amorphous organic material, celled plant material

Table 5.20. Results for the organic material, identified through soil micromorphological analysis, based on the protocol used for the CDB.

Sutton Common Sample Name	Amorphous		Charcoal < 100µm	Charcoal > 100µm	Celled			Plectenchyma (Fungi)	Pollen
	Punctuations	Matter			Lignified	Parenchymatic	Phlobaphene		
SC2003 107a	■■■■■■■■	■■■■■■■	■■■■■	■■■	■ 3-5				■
SC2003 107b	■■■■■■	■■■■	■■■	■	■ 3		■ 3		
SC2003 106a	■■■■	■■■	■■■	■		■ 2-3			
SC2003 106b	■■■	■■	■■■	■■					
SC2003 105	■■■	■■	■■	■					
SC2003 118a	■■■■■	■■■■■	■■■■	■■					■
SC2003 118b	■■■	■■	■						
SC2003 119a	■■■■	■■■	■■■	■■					
SC2003 119b	■■■	■■	■■■	■					
SC2003 120a	■■■■■■	■■■■■	■■■■	■■■					
SC2003 120b	■■■■■	■■■■	■■■	■					
SC2003 120c	■■■■	■■■	■■■	■■					
SC2003 5001	■■■■■■■	■■■■■■	■■■	■■	■ 3-5	■ 3-5			
SC2003 5002	■■■	■■	■■■	■					
SC2003 5003	■■■■■■	■■■■■	■■■	■	■■ 2-5				
SC2003 5004a	■■■■■	■■■■	■■■	■	■■ 3-5	■ 3-5	■ 3		■
SC2003 5004b	■■■	■■	■■■	■					

Key: ■ <2%, ■■ 2-5%, ■■■ 5-10%, ■■■■ 10-20%, ■■■■■ 20-30%, ■■■■■■ 30-40%, ■■■■■■■ 40-50%, ■■■■■■■■ 50-60%, ■■■■■■■■■ 60-70%

Key to the preservation of organic material: 1 = fresh; 2 = yellow; 3 = red-brown; 4 = brown; 5 = black

and charcoal in the Ap horizon, and an iron- and clay-rich B horizon, with a decrease in organic material (table 5.20). Further, there is some mixing of the B horizon in the lower part of the Ap, which suggests disturbance between these layers. Iron coatings of grains and voids are present throughout the profile but are present in high quantities in the subsoil material (table 5.21). In addition, iron replaced organic material is only present in small quantities in the subsoil (table 5.21), which suggests that the groundwater table was fluctuating at this level some time in the past, and would also account for the distinctive iron mottling in this horizon. The buried A horizon is highly organic with amorphous organic material dominating, and some mildly to well decayed celled plant material present (table 5.20). As suggested from the field descriptions, there is a transition layer (Bh) between the buried A horizon and the underlying C horizon, which is evident through the presence of amorphous organic material and moderately to well decayed celled plant material. The underlying C horizon has a dramatic decrease in organic material, and the organic material present is amorphous and in the last stage of decomposition.

Table 5.21. The average percentage of iron coatings of voids and grains, and of iron replacement of organic material identified through micromorphological analysis.

Sutton Common Sample Name	Coatings of Grains and Voids (%)	Replacement of Organic Matter (%)
SC2003 107a	8	<2
SC2003 107b	2	
SC2003 106a	4	<2
SC2003 106b	3	<2
SC2003 105	21	
SC2003 118a	1	
SC2003 118b	10	
SC2003 119a	8	<2
SC2003 119b	8	
SC2003 120a	3	
SC2003 120b	1	
SC2003 120c	3	
SC2003 5001	3	
SC2003 5002	14	<2
SC2003 5003	5	
SC2003 5004a	4	
SC2003 5004b	3	

Samples 118 and 119, taken from the first posthole, include the organic-rich fill of the feature (118a), the leached but iron mottled sediment immediately surrounding the organic-rich fill

(118b), a clay- and iron-rich sediment (119a), followed by a leached, iron mottled sediment (119b). 118a is most likely the remnants of the decomposed wooden post, which decayed once oxygen was introduced into a previously waterlogged site. The leached sediment immediately surrounding this organic fill has some orientation but a very low quantity of clay and organic material (table 5.20). There is an increase of iron coatings of grains and voids in 118b, which suggests some degree of illuviation and may be the result of post-depositional processes. Layers 119a and 119b are indicative of the natural soil surrounding the feature. 119a is rich in iron and clay and has a higher clay component than 119b, which appears to be more leached of the fine soil components, including organic material. 119a also has small amounts of iron replaced organic material and a higher proportion of iron coatings than 119b (table 5.21). As these sediments are horizontally related, the differences between 119a and 119b are most likely the result of variations in iron oxide mottling of the sediment. In the case of 119a, the heavily iron impregnated fabric has "trapped" the finer components of the fabric, such as organic material and clay, preventing the leaching of this material from the sediment. However, the absence of such extensive iron impregnation in 119b has resulted in the majority of the fine material being leached out.

The sample from the second posthole (120) shows three distinct layers: the first, the organic remnants of the wooden post (120a), evident through the presence of large pieces of cellular plant material and charcoal; the second, a clearly orientated, predominantly clay sediment (120b); and third, an iron mottled sediment (120c) similar to the sediments identified in the first posthole, and most likely a natural sediment. The clear orientation of the clay-rich sediment of 120b suggests that the sediment may have been used to line the posthole, or that the sediment has been affected by water flowing through the sediment. Given the presence of this material around all the posthole features at the site (Ayala 2003), it is most probable that this sediment was used during the construction of the feature. Further, given the orientation of the sediment, it seems unlikely that this material was the result of natural infilling of the posthole feature. There are very few iron coatings of grains and voids in any of the sediments from 120, which suggest that illuviation processes in this feature were not predominant (table 5.21). In addition, the dominant organic material present in 120 is amorphous punctuations and fine amorphous organic matter (table 5.20). This suggests that oxidation has had a strong effect on the preservation of the organic material present in 120. There is also a decrease in organic material away from the centre of the posthole, which is expected given the nature of the feature and sediments sampled.

Finally, iron staining and iron nodules are also present in each of the sediments sampled at Sutton Common, and the relative percentages of these types of iron oxide deposition are presented in figure 5.22 below. The complex hydrological history of the Iron Age enclosures at Sutton Common would suggest a mixed trend in patterns of iron oxide deposition. As the site has been recorded in the recent past as being largely waterlogged with a high fluctuating groundwater table, one would expect iron staining to predominate (Caple and Dungworth 1997; Chapman and Cheetham 2002; Parker Pearson and Sydes 1997; Van de Noort *et al.* 2001). However, the more recent irrigation and water abstraction within the vicinity of the site has significantly lowered the local groundwater table at Sutton Common and has had devastating effects on the preservation of the organic remains (*ibid*). This sudden lowering of the groundwater table and rapid oxidation of the sediments results in the formation of diffuse iron nodules, as discussed in previous chapters.

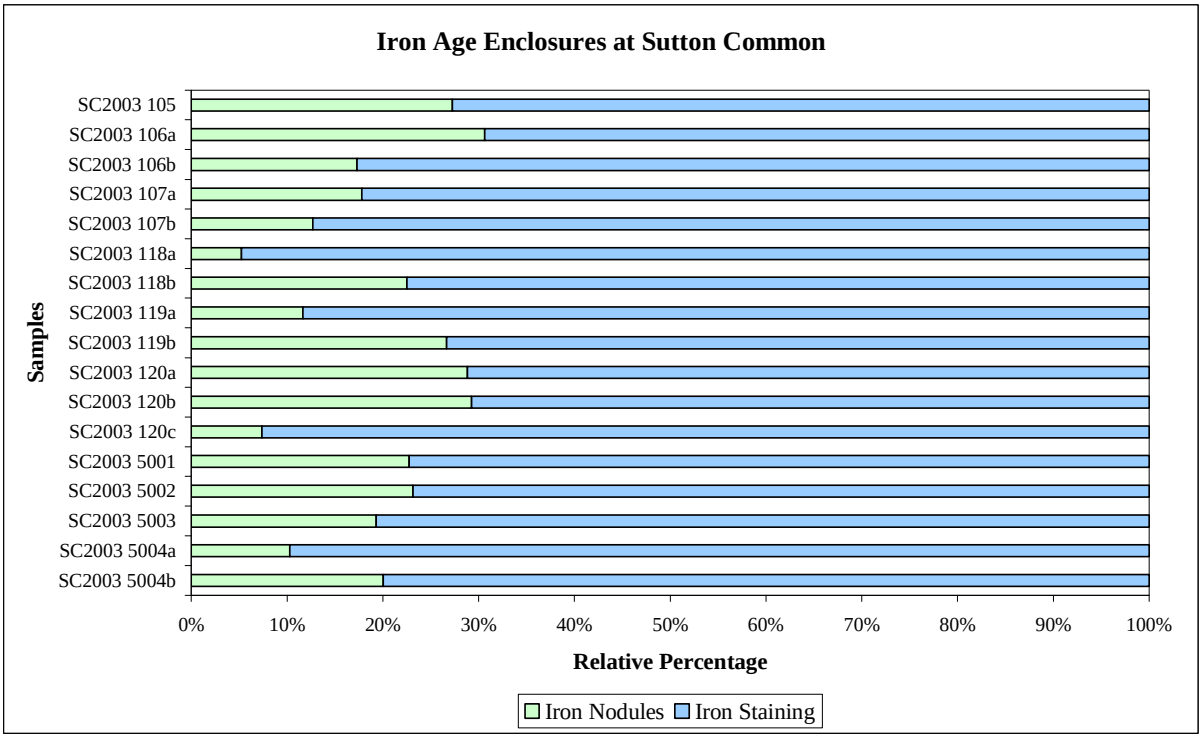


Figure 5.22. The relative percentage of iron nodules versus iron staining present in the samples collected from Iron Age enclosures at Sutton Common.

As figure 5.22 illustrates, iron staining predominates over iron nodules with proportionately low frequencies of diffuse iron nodules present in the sediments analysed. This suggests that in spite of the dramatic lowering of the groundwater table and subsequent rapid oxidation of the sediments, the impermeable nature of the clay-rich sediment at Sutton Common may have held the soil moisture over a longer period of time, effectively slowing down the oxidation of the sediments, resulting in the predominance of iron oxide staining over iron nodules. This

suggests that the variation in iron oxide deposition is dependent on the type of soil/sediments present.

5.6 Bronze Age Field Systems at Shovel Down

The Bronze Age field systems at Shovel Down are situated on the moorlands within the Gidleigh Parish and Dartmoor Forest, north-east Dartmoor, on the watershed between the North and South Teign Rivers (SX 655 860) in Devon (figure 5.23) (Brück *et al.* 2003). The local soil profile is identified as a stagnopodzol with intermittent gleyed horizons and a typical sequence of humose/peaty and peat/peaty topsoil layers overlying a leached and gleyed mineral horizon, followed by an occasional iron pan and iron-rich B horizon, with a Dartmoor Granite bedrock (Lewis 2004b, 8). This fits with the standard description of a stagnopodzol, which is defined as a soil with peaty topsoil, periodically wet (gleyed) bleached horizon, or both, over a thin iron pan and/or a brown or ochreous, relatively friable, subsurface horizon (Courtney and Trudgill 1976, 101).



Figure 5.23. View across the moorlands at Shovel Down, Dartmoor, Devon.

The Shovel Down Project consists of archive research, extensive survey, and excavation of target areas, and aims to investigate the chronology and land use history related to the Bronze Age field systems, using both archaeological and palaeoenvironmental approaches (Brück *et al.* 2003; Johnston *et al.* 2003; Lewis 2004b). Micromorphology samples were collected during the 2003 excavations by Lewis in order to "assess the potential for understanding the meaning and role of ancient land use" by identifying buried soils and investigating the sedimentary processes associated with walled coaxial field systems (Lewis 2004b, 1). The result of this initial sampling revealed one buried soil layer identified beneath leat 1 (an open watercourse) with the remainder proving to be examples of the modern soil horizon or colluvial deposits (*ibid*). There is, however, evidence of relatively stable, long-term pedogenesis and further investigations are being undertaken to identify micro-indicators of past land use.

Table 5.22. The soil micromorphology and bulk samples collected from the Bronze Age field systems at Shovel Down, along with their field description and context.

Micromorphology Sample*	Field Description and Context	Associated Bulk Sample
SDP04 T2 960/2034a	grey layer - silty clay loamy material	SDP04 T2 960/2034 <6>
SDP04 T2 960/2034b	orange layer - sandy clay; charcoal throughout orange layer; possible posthole with large chunks of charcoal (*c* .3cm)	SDP04 T2 960/2034 <7>
SDP04 T4 5000/6100 <2> a	dark grey layer - silty/peaty like layer	SDP04 T4 5000/6100 <3>
SDP04 T4 5000/6100 <2> b	loamy clay - fill of possible feature; cut is marked by Fe pan	SDP04 T4 5000/6100 <4>
SDP04 T4 5000/6280 (3) <3> a	taken across peaty/silty layer between two orange-brown layers - mineral-rich layer	SDP04 T4 5000/6280 <2>
SDP04 T4 5000/6280 (3) <3> b	taken across peaty/silty layer between two orange-brown layers - peaty layer/ Fe-organo-clay-rich layer	SDP04 T4 5000/6280 <1>

* a and b signify separate units identified by soil micromorphology in the same sample

In 2004, a number of test pits were excavated along transects across the site to investigate areas that are archaeologically rich, and can be targeted for more detailed excavations in the future. From the test pits available, three were identified with possible features relating to iron oxide deposition and were selected for sampling. A total of three micromorphological samples and six small bulk samples for bulk analyses were collected to assess the effectiveness of using iron oxide deposition as a sensitive indicator of oxidation, and how this affects the preservation of organic material within an archaeological context (table 5.22).

The first test pit sampled was transect 2 E960 N2034 with a profile of dark grey to black peaty soil, overlying grey silty clay loam, followed by an iron pan and orange sandy clay with

large pieces of charcoal (*c.* 3cm). It is possible that this profile contained a posthole, although further excavation is necessary. A micromorphology sample was taken across the grey silty clay loam layer, the iron pan and the orange sandy clay beneath (table 5.22 and figure 5.24). Bulk samples were collected from the grey layer and the orange layer, above and below the iron pan, respectively.

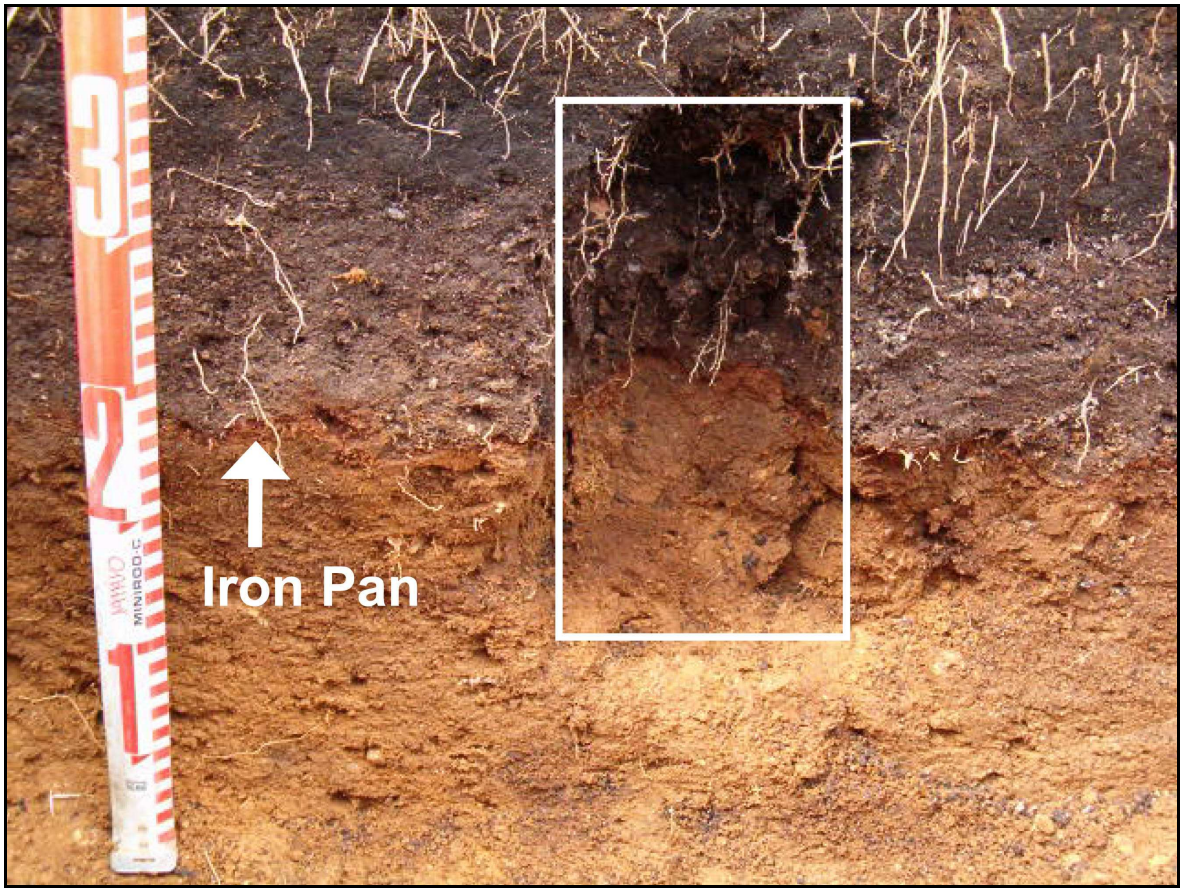


Figure 5.24. The soil profile of transect 2 E960 N2034 with the location of the micromorphology sample collected in 2004.

The second test pit sampled was transect 4 E5000 N6100 with a profile consisting of peaty soil overlying a dark grey organic-silty layer, followed by a grey loamy clay and the orange sandy clay 'natural' layer. This test pit contained a possible feature with the grey loamy clay being the primary fill of this feature. An iron pan lined the cut of the feature at the bottom left corner of the test pit (table 5.22 and figure 5.25). The micromorphology sample was taken across the grey loamy clay (primary fill) layer and the dark grey organic-silty layer above, along with bulk samples from both these layers.

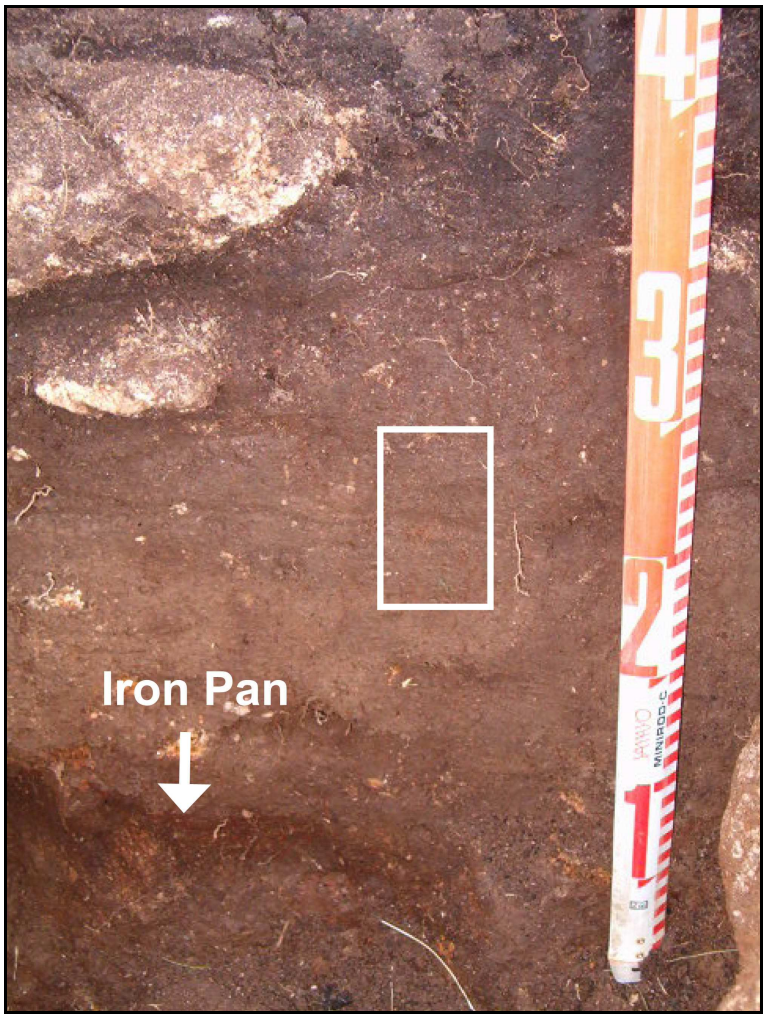


Figure 5.25. The soil profile and possible feature in transect 4 E5000 N6100 with the location of the micromorphology sample collected in 2004.

The third test pit sampled was transect 4 E5000 N6280 and contained iron panning above and below a possible ditch feature, which may be associated with a stone built wall nearby. The fill contained alternating layers of silty organic peat-like sediment and orange-brown sandy clay, reminiscent of the site's 'natural' soil. The micromorphology sample was taken across one of the orange-brown sandy clay layers and its subsequent silty organic peat-like layer (table 5.22 and figure 5.26).

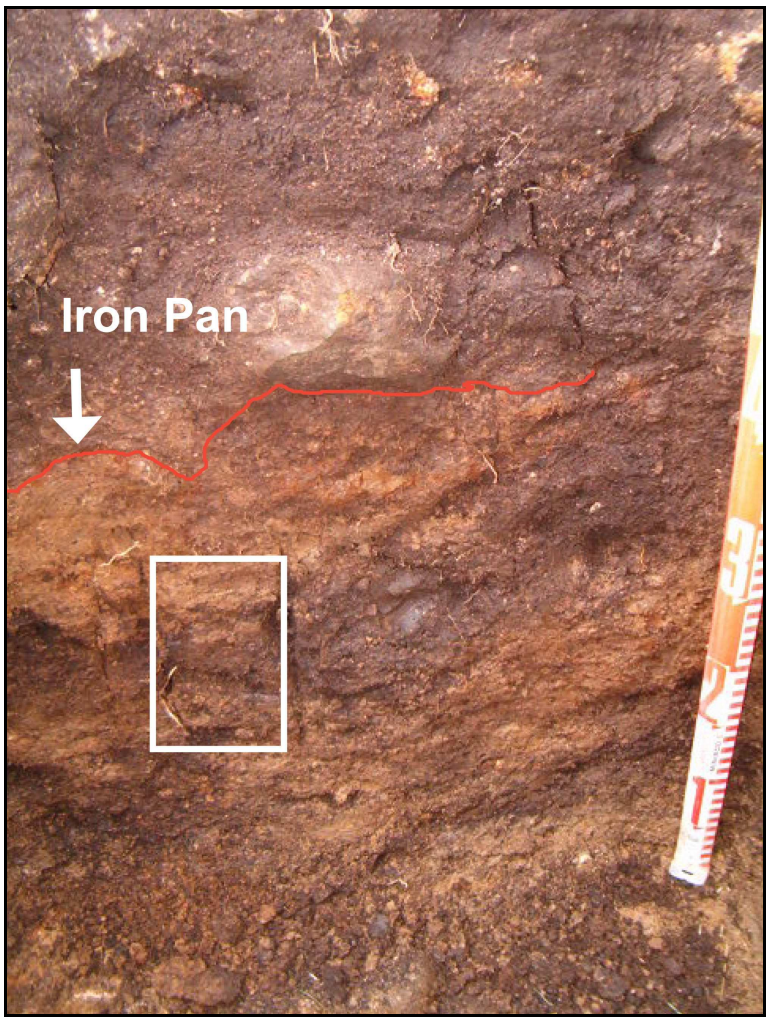


Figure 5.26. The soil profile and possible ditch fill in transect 4 E5000 N 6280 with the location of the micromorphology sample collected in 2004. The iron pan above the feature has been outlined in red.

At the time these samples were collected, permission to excavate at the site was limited to test pits only, and therefore, it was difficult to identify specific features and their relationships within the site. Further excavation was planned for targeted areas based on the results of the test pit excavations in 2004.

5.6.1 Bulk Analyses Data

The bulk samples collected in 2004 were analysed by a suite of bulk analyses techniques, including ICP-AES for total Fe and Mn, LOI for %Water and %OM, PSD for %Clay, MS, pH, EC and redox. In addition, in-field moisture readings were taken to measure volumetric water content (VWC), and moisture content was measured for soil moisture content prior to air drying the sediments for the bulk analyses listed above. The results of these analyses are presented in table 5.23 below.

Table 5.23. Results for the bulk analyses carried out on the bulk samples collected from the Bronze Age field systems at Shovel Down; MC = moisture content.

Sample	Context	Fe (ppm)	Mn (ppm)	%Water (LOI)	%OM (LOI)	%Clay (PSD)	MS (x10 $^{-8}$ (m^3/kg))	pH	EC	Redox	MC (%)	VWC (%)
SDPT4/1	Silty clay layer	19300	219	3.09	10.62	5.21	0.49	4.68	57.67	232.00	15.86	42.33
SDPT4/2	Fe rich layer	22700	214	2.35	6.22	4.40	0.66	5.00	22.00	218.00	11.02	28.00
SDPT4/3	Silty/peaty layer	4000	42	1.84	7.49	7.45	0.12	4.62	35.00	257.00	15.58	21.00
SDPT4/4	Feature fill	6700	63	1.92	6.00	12.61	0.22	4.75	21.33	251.00	18.62	17.67
SDPT2/6	silty clay loamy layer	5000	40	2.25	9.27	11.77	0.17	4.98	29.33	245.00	23.45	25.67
SDPT2/7	sandy clay layer	29200	556	2.97	7.43	9.21	1.89	5.05	14.67	240.33	19.42	21.33

Table 5.24. Results from ICP-AES for the plant nutrients present in the samples collected from the Bronze Age field systems at Shovel Down.

Shovel Down	Plant Macro-Nutrients							Plant Micro-Nutrients						
Sample Name	Al (ppm)	Ca (ppm)	Fe (ppm)	K (ppm)	Mg (ppm)	P (ppm)	S (ppm)	B (ppm)	Co (ppm)	Cu (ppm)	Mn (ppm)	Mo (ppm)	Na (ppm)	Zn (ppm)
SDPT4/1	14500	1500	19300	3200	2000	450	500	<10	3	6	219	1	300	24
SDPT4/2	20000	1900	22700	3800	3600	630	300	<10	4	8	214	1	300	40
SDPT4/3	6700	200	4000	1100	400	250	300	<10	1	3	42	<1	200	9
SDPT4/4	9400	100	6700	1300	600	210	300	<10	1	3	63	<1	200	13
SDPT2/6	7500	100	5000	800	300	200	400	<10	<1	3	40	1	200	11
SDPT2/7	15900	200	29200	1600	1500	340	400	<10	3	5	556	1	200	27

The bulk analyses results for T4/1, taken from the peaty/silty sediment in test pit T4 5000/6280, has high OM content, moisture levels (%Water, moisture content and VWC) and EC values, indicating this sediment is organic-rich and comparatively rich in soluble salts, which is consistent with its peaty nature. T4/2 is comparatively poorer in organic material, moisture content and soluble salts, but higher in other soil nutrients (table 5.24) and total Fe with slightly higher MS values. The increase in Fe is expected given the orange colour of the sediment, and the increase in MS indicates that the Fe present may be magnetically charged. Both sediments have similar quantities of Mn with T4/1 slightly higher than T4/2, indicating that Mn has little bearing on the MS results. Additionally, T4/1 and T4/2 have less than 5.5% clay with a slight increase in clay content in T4/1. This corresponds to the micromorphology analyses, which revealed a fabric with high quantities of gravels and very coarse sand-sized grains and low clay content. Both sediments are acidic and moderately reducing with slightly higher pH values in T4/2, indicating that the sediment with higher organic content is more acidic. There is a discrepancy between the moisture content and VWC results with VWC measurements being higher than moisture content measurements. The reason for this is unclear but may represent localised *in situ* moisture pockets within the sediments.

The bulk analyses results for T4/3, taken from the dark grey peat-like layer in test pit T4 5000/6100, and for T4/4 taken from the primary fill of the possible feature, are quite similar except for a slight increase in total Fe, Mn and %Clay in the feature fill. This increase in Fe and Mn is coupled with a slight increase in MS, albeit the values are low. This indicates that the iron present is magnetically susceptible and is mostly likely being held in the clay component of the sediment. This is supported by the micromorphological analyses below. T4/3 is slightly richer in organic material and has slightly elevated EC values, which correspond to its peat-like nature. Both sediments are acidic and moderately reducing but there is a discrepancy between the moisture content and VWC results for T4/3 with VWC indicating significantly higher levels than moisture content. It is unclear why this discrepancy has occurred but it may be the result of *in situ* localised moisture pockets within the peat-like sediment, as organic-rich sediments are more likely to retain moisture than more freely draining sediments.

The bulk analyses results for T2/6 and T2/7, taken from the profile of test pit T2 960/2034, indicate a movement of iron and manganese down profile to form the iron pan, which separated the two sediments, illustrated by the low Fe and Mn values for T2/6 and elevated values for T2/7. There is also a significant increase in MS readings in T2/7, which reflects the

elevated Fe and Mn values in this layer. In addition, there is an increase in other soil nutrients in T2/7, which suggests some movement of these minerals down profile, either prior to, or during, iron pan formation (table 5.24). These minerals may have also contributed to the increased MS values for this layer. The presence of this iron pan has prevented the leaching of organic matter and clay from the sediment, as indicated by the comparatively elevated %OM and %Clay results for T2/6. In addition, the EC values are higher in T2/6, which corresponds to more clay and organic-rich sediments (Carroll and Oliver 2005). Both sediments are acidic and moderately reducing with an increase in moisture (moisture content and VWC) in the upper layer. This is not surprising given the organic nature of the sediment and the water retaining ability of organic material.

5.6.2 Soil Micromorphology

Soil micromorphological analyses were carried out on the samples collected from Shovel Down following the same protocol used for the CDB sites. The results of these analyses are presented in appendix F, tables 5.25 and 5.26, and figure 5.27 below.

The micromorphology sample collected from T4 5000/6280 has two distinct layers: 3a and 3b. The former is an iron-rich mineral layer with poorly sorted sediment, including grain sizes from fine gravel to fine sand. The latter sediment is organic-rich with equally poor sorting but with a larger proportion of fine material than in 3a (appendix F). 3b is dominated by amorphous organic punctuations and amorphous organic matter (table 5.25). There is evidence of some celled plant material but this material is poorly preserved, as well as clusters of plectenchyma (fungi), which is typically found in organic-rich topsoils but can be found lower down the soil profile (table 5.25) (FitzPatrick 1984). Layer 3a has very little organic material and the organics that are present are punctuations (<1µm) with some fine amorphous matter (>1µm) and plectenchyma (table 5.25). Phytoliths of various shapes were also observed in both layers. There is some iron replacement of organic material in 3a (table 5.26), which suggests that redox processes have occurred; however, given the lack of fluctuating groundwater, it is more likely that these redox processes are the result of microbial activity. Iron coatings of grains and voids are also present in both 3a and 3b, with slightly more in 3b (table 5.26). This could be the result of illuviation processes with iron-rich clay being eluviated from 3a and illuviated down profile in 3b, which would support earlier observations made by Lewis (2004), who indicated that the soil profiles at Shovel Down are generally stagnopodzols.

Table 5.25. Results for the organic material, identified through soil micromorphological analysis, based on the protocol used for the CDB.

Shovel Down	Amorphous		Charcoal	Charcoal	Celled			Plectenchyma	Pollen
Sample Name	Punctuations	Matter	< 100µm	> 100µm	Lignified	Parenchymatic	Phlobaphene	(Fungi)	
SDP04T2 960/2034a	■■■■■■	■■■■	■■	■	■ 1	■■ 1-2		■■ 3	■■■
SDP04T2 960/2034b	■■■■■■	■■■■	■■	■		■ 3-5		■■ 3-5	■■
SDP04T4 5000/6100 <2>a	■■■■■■■■	■■■■■	■■	■	■■ 2-3	■■■■ 2-3	■■■■ 2-3	■■■■ 3-5	
SDP04T4 5000/6100 <2>b	■■■■■■■	■■■■	■■■	■	■ 2-3	■■■ 2-3	■■■■ 2-3	■■■■ 3-5	
SDP04T4 5000/6280 (3) <3>a	■■■■■■	■■■■	■■■	■				■■ 3-5	
SDP04T4 5000/6280 (3) <3>b	■■■■	■■■■■	■■■	■	■ 3	■■ 3-5	■ 3	■■■■■ 3-5	

Key: ■ <2%, ■■ 2-5%, ■■■ 5-10%, ■■■■ 10-20%, ■■■■■ 20-30%, ■■■■■■ 30-40%, ■■■■■■■ 40-50%, ■■■■■■■■ 50-60%, ■■■■■■■■■ 60-70%

Key to the preservation of organic material: 1 = fresh; 2 = yellow; 3 = red-brown; 4 = brown; 5 = black

Table 5.26. The average percentage of iron coatings of voids and grains, and of iron replacement of organic material identified through micromorphological analysis.

Shovel Down Sample Name	Coatings of Grains and Voids (%)	Replacement of Organic Matter (%)
SDP04T2 960/2034a	7	<2
SDP04T2 960/2034b	31	<2
SDP04T4 5000/6100 <2>a	5	
SDP04T4 5000/6100 <2>b	11	
SDP04T4 5000/6280 (3) <3>a	19	<2
SDP04T4 5000/6280 (3) <3>b	27	

The micromorphology sample collected from T4 5000/6100 was taken across two layers, 2a and 2b, of a possible feature lined by an iron pan. Both layers show signs of biological activity via roots and rootlets, and earthworm activity, indicated by decomposing organic matter in pore spaces for the former, and a 'trail' of well sorted very fine sand and clay sediment running obliquely across 2a for the latter. Both fabrics are generally poorly sorted with very coarse sand-sized grains to very fine sand-sized grains making up the coarse fraction of the fabrics. Both sediments are rich in organic material with organic punctuations and fine amorphous organic matter predominating (table 5.25). Celled plant material is also present with various stages of decomposition as well as plectenchyma in both layers (table 5.25). Layer 2a has slightly more organic material than 2b, which corresponds to the bulk analyses and is consistent with the peaty nature of the sediment described in the field (tables 5.23 and 5.22). There is no iron replacement of organic material present in either layer but iron coatings of grains and voids are present with an increase in 2b, suggesting illuviation of iron-rich clay down the soil profile (table 5.26). There were no anthropogenic pedofeatures found in the fill layer (2b), although given the acidic nature of the sediment, it is unlikely that inclusions, such as bone, would survive. Phytoliths were observed in both sediment layers and it would be worth investigating these further to identify plant species; however, this is outside the scope of my research.

The micromorphology sample collected from T2 960/2034 was taken across two layers divided by an iron pan. Both layers are poorly sorted with a range of grains from fine gravel to very fine sand-sized coarse fraction, although the lower layer has a slightly higher proportion of coarse material to fine material. The upper layer contains both amorphous organic material in the form of punctuations and fine amorphous organic matter, and celled plant material, which is relatively well preserved (table 5.25). The lower layer is dominated by organic punctuations and fine amorphous organic matter with very little poorly preserved celled material (table 5.25). This is also reflected in the bulk analyses (table 5.23). Plectenchyma and pollen are also present in both layers with slightly better preservation in the upper layer. Iron replaced organic material is present in both layers and is most likely the result of both microbial activity and iron pan development, causing localised *in situ* reducing conditions (table 5.26). Iron coatings of voids and grains are also present in both layers with a significant increase in the lower layer, indicating the illuviation of iron-rich clay down profile, which supports the bulk analyses results and the process of iron pan formation through podzolisation.

The sediments from the upper layer of T2 960/2034 and layer 2a from T4 5000/6100 are similar in composition, and are most likely the Oh horizon of the typical soil profile at the site noted by Lewis (2004, 8). That is, humose/peaty topsoil (Ah/Oh) overlying peat/peaty topsoil (O/Oh), followed by a leached and gleyed mineral horizon (Eag), an occasional iron pan (Bfe), and an iron-rich B horizon (Bs & Bs/C) (*ibid*). It is highly possible that layer 2b is the fill of the feature outlined by the iron pan, as this sediment does not reflect the general soil profile observed at Shovel Down. The profile of T2 960/2034 appears to be typical of the podzolic soil at Shovel Down, and although there was some charcoal in the micromorphology sample (table 5.25), further investigation is necessary to identify the presence of the posthole feature. The sediments from T4 5000/6280 are more puzzling, and could be the result of colluvial build-up as the test pit is situated on a hillslope. This phenomenon is repeatedly observed by Lewis (2004), and without further excavation to find the cut of the possible feature, it is difficult to assess at this time.

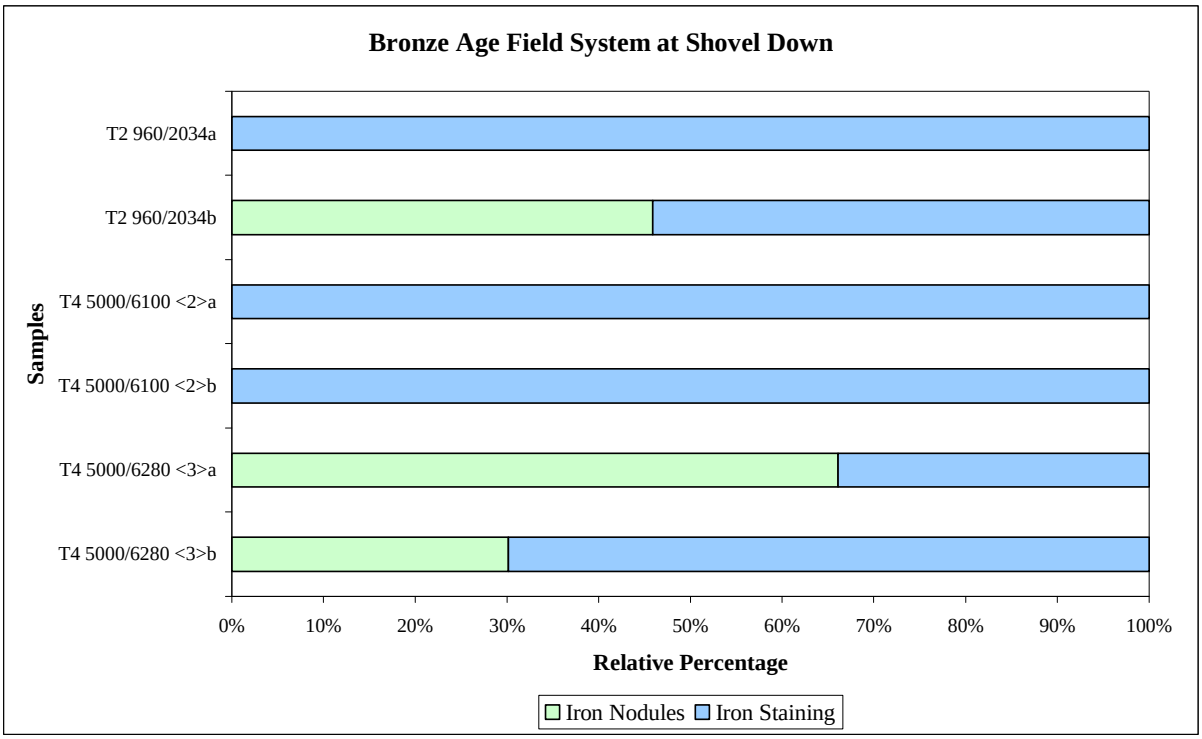


Figure 5.27. The relative percentage of iron nodules versus iron staining present in the samples collected from the Bronze Age field systems at Shovel Down.

Finally, both iron nodules and iron staining were observed in the samples collected from Shovel Down, although there is a significant predominance of iron staining in most of the samples analysed (figure 5.27). Given the podzolic nature of the sediments at this site, it is not surprising that iron staining dominates, as the process of podzolisation is a slow, long-term process that can take decades (Breuning-Madsen and Holst 1992). Further, the lack of a

fluctuating groundwater table limits the possibility of rapid oxidation taking place through mechanical de-watering, as in other sites presented in this chapter. However, it is clear that reducing conditions do exist at the site as many gleyed horizons have been observed by Lewis (2004), and the soil profile at Shovel Down has been described as a stagnopodzol (*ibid*). The development of these gleyed conditions is most likely the result of microbial activity, compounded by the compaction from the stone built walls and colluviation evident at the site (*ibid*). The increase in nodules in layers T2 960/2034b and T4 5000/6280a is indicative of the iron-rich nature of these layers, which are representations of the site's 'natural' sediment and is most likely the result of localised hydrological changes taking place at Shovel Down.

5.7 SUMMARY

The introduction of an archaeological context to the CDB, in order to test the effectiveness of using iron oxide deposition as a sensitive indicator of the hydrological/oxidation conditions present within a site, has been assessed in this chapter. The micromorphological and bulk analyses results for five archaeological sites have been presented and discussed here on a site by site basis.

At the Late Bronze Age enclosure at Over, the analyses revealed that the presence of iron panning beneath each of the features, formed prior to gravel extraction and most likely as the result of a fluctuating groundwater table, has protected the sediment from leaching processes due to the mechanical and rapid lowering of the groundwater table via water abstraction. Further, the general predominance of iron nodules over iron staining reflects the rapid introduction of oxygen as a result of water abstraction ahead of gravel extraction.

The Iron Age ringwork at Wandlebury contained a variety of remains preserved, including human bones, charred and mineralised plant remains, and both burnt and unburnt faunal remains. In the samples from the counterscarp bank, iron nodules are predominant, suggesting rapid oxidation possibly from past arable use, the mechanical mixing of the soil, which occurred during the construction of the bank, and/or the evident bioturbation. In the samples from the inner rampart, iron staining is predominant, most likely the result of organic decomposition via microbial activity and localised redox processes.

The results from the Romano-British site at Marcham-Frilford reflect the local hydrological environment with a predominance of iron staining suggesting slow oxidation, which reflects

the local fluctuations of the groundwater table. In addition, the organic preservation is quite good at the site with wood and charcoal being well preserved as well as biominerals, such as bone.

The predominance of iron staining over iron nodules in the samples collected from the Iron Age enclosures at Sutton Common also reflects a hydrological environment of a naturally fluctuating groundwater table. However, the site has undergone rapid oxidation from irrigation and water abstraction off-site, and therefore, the predominance of iron nodules would be expected. The impermeable nature of the clay-rich sediments at the site and the excellent organic preservation, suggest that water was retained within the sediment for a longer period of time and may have resulted in a slow rate of oxidation of the archaeological sediments. This, in turn, could be responsible for the good preservation of organic material until recently.

Finally, the iron oxide deposition in the samples from the Bronze Age field systems at Shovel Down indicate a predominance of iron staining over iron nodules, which represents the hydrological/oxidation environment present at this site. That is, the site is characterised by a stagnopodzol, which is a long term process involving eluviation of fine material from upper horizons and subsequent illuviation of fine material in the lower horizons (Curtis *et al.* 1976). In addition, localised gleyed horizons form by reducing conditions caused by the impermeable nature of the sediments (*ibid*) (e.g. iron pans). These slow oxidation (and reduction) processes are reflected in the predominance of iron staining in the sediments at Shovel Down.

After assessing the different types of iron oxide deposition in both the experimental sites that form the CDB (chapter four) and the archaeological sites with similar soil/geology types (chapter five), the next chapter will assimilate this data and argue for the application and limitations of using the CDB as a gauge for the preservation of organic material in archaeological sites. The potential for using the CDB as a tool in the planning process for preservation and conservation of archaeological sites for future generations will also be discussed in chapter six.

– 6 –

APPLYING THE CDB TO GAUGE THE PRESERVATION OF ARCHAEOLOGICAL MATERIAL DATA

6.1 INTRODUCTION

Identifying a tool for gauging the likely preservation of archaeological organic material in buried environments is paramount to archaeological conservation research. This research has shown that the deposition patterns of iron oxidation can be a sensitive indicator of changes in the oxidation conditions within a buried environment, and can be an effective way of gauging the preservation environment of organic material in archaeological sites. The study has included the analysis of soils and sediments from both non-archaeological and archaeological sites of varying soil/geology types within Britain, including an alluvial brown earth, a typical rendzina, an argillic pelosol and a brown podzolic soil. This chapter will first identify the type of iron oxide pedofeatures present at the sites used to build the comparative database (CDB), and will discuss the use of iron oxide as a sensitive indicator for gauging preservation conditions. The practical application of the comparative database (CDB) will then be outlined, followed by a discussion on how this information can be used as part of the planning process in relation to archaeological conservation. Finally, a discussion on the use of the CDB for determining a preservation timescale will be presented.

6.2 A SENSITIVE INDICATOR FOR GAUGING PRESERVATION

The previous chapters have identified two types of iron oxide deposition, which prove most informative for determining the hydrological/oxidation conditions of a buried environment: iron nodules and iron staining. The main processes responsible for these deposition patterns are cycles of reducing-oxidising conditions within the soil, otherwise known as redox

processes. Redox processes most commonly occur due to fluctuations of the groundwater table but they can also be produced by microbial activity. The decomposition of organic material produces localised, highly acidic and reducing conditions in which anaerobic micro-organisms oxidise minerals, such as iron, during respiration and consumption.

There are many different types of iron oxide (and hydroxide) minerals, as outlined in chapter two and table A-2 in appendix A; however, given the climate and hydrological environment of the sites chosen for this research, the iron oxides present are most likely ferrihydrite or lepidocrocite. Lepidocrocite is present in acidic, temperate and subtropical hydromorphic soils and is formed by redox processes (Kapička and Petrovský 2003; Loeppert and Inskeep 1996; Stucki *et al.* 1988). It is moderately magnetic and usually forms in soils that are low in organic material (*ibid*). Ferrihydrite is found in most soils in minor quantities but is a major component of fluctuating redox environments, and often forms in the presence of organic material (*ibid*). Although there is little known about this mineral, the crystal structure indicates that it is the result of rapid oxidation and it has low magnetic properties (*ibid*). It is present in both alkaline and acidic soils, although the processes of oxidation differ depending on the pH of the environment. In neutral to alkaline soils, the oxidation of ferrihydrite is most likely from fluctuating groundwater conditions, while in acidic environments microbial activity is responsible (*ibid*).

The four sites chosen for the compilation of the CDB can be divided into two separate groups: one which is influenced by groundwater movement, and the other which has no evidence of groundwater influences. Wandlebury, a rendzina on a chalk substrate, and Sherwood, a brown podzolic soil, have no direct groundwater influences and are rich in organic material. At these sites redox processes are evident (iron replacement of organic material), probably due to microbial respiration and consumption of decaying organic material, and the release of minerals during decomposition, including iron. At Sherwood, there is additional evidence for leaching processes in the form of iron-rich illuvial clay coatings in the Bts horizon. In addition, the acidity of the site and the lack of groundwater, at Sherwood, strongly suggest that ferrihydrite is the most dominant form of iron oxide present. However, the neutral to alkaline conditions and the unusually high magnetic susceptibility of the soils from Wandlebury, along with the land use history of the site, suggest that magnetite or maghemite are likely to be present, and that burning has transformed the iron oxide into a highly magnetic form (French *et al.* 2005b; Loeppert and Inskeep 1996; Stucki *et al.* 1988).

Over, an alluvial brown earth, and Savernake, an argillic pelosol, are both influenced by groundwater fluctuations and show clear evidence of redox processes, including iron replacement of organic material, iron staining, and iron nodules. In addition, eluviation/illuviation of iron-rich clay is evident at both sites, with Over suffering from a dramatic loss of organic material associated with the rapid lowering of the groundwater table, due to gravel extraction in the vicinity of the site. In contrast, Savernake does not suffer from this degree of leaching, as reflected in the presence of celled organic material, availability of soluble salts and a prominent fine soil fabric of silty clay. In addition, the acidic nature of Savernake suggests that lepidocrocite is likely to be predominant and that ferrihydrite is likely to be present in the more organic-rich soil horizon. At Over, oxidation resulting from groundwater fluctuations is responsible for the predominance of ferrihydrite. Given that ferrihydrite is also the result of rapid oxidation, this scenario fits well with the rapid lowering of the groundwater table ahead of gravel extraction.

The oxidation experiments revealed that iron staining was predominant in the air dried samples, which replicated slow oxidation conditions, and iron nodules were predominant in the oven dried samples, which replicated rapid oxidation. The effect of rapid oxidation versus slow oxidation on the preservation of organic material is a complex issue. At sites, such as Sherwood and Wandlebury, which are not influenced by groundwater but are highly oxidised soils, the preservation of organic material is poor. Additionally, the leaching processes involved in the development of podzolic soils are detrimental to organic preservation, just as the biological activity and subsequent oxidation and organic decomposition, present in rendzinas, is not conducive to the preservation of organic material. These poor preservation conditions are also reflected in the archaeological sites chosen to test the CDB sites of Wandlebury and Sherwood, and include Wandlebury Iron Age ringwork for the Wandlebury CDB site, and Shovel Down and Sutton Common for the Sherwood CDB site.

Wandlebury had very good preservation of both human skeletal and faunal remains, as is expected in a calcareous burial environment, but poor preservation of uncharred plant remains (French *et al.* 2005b). The results of the CDB site also indicated poor preservation of plant remains, with the remains that were present in more advanced stages of decomposition. This level of organic preservation reflects the oxidised, calcareous environment present at Wandlebury. The preservation at Sherwood varied down profile with obviously good preservation of organic material in the O horizon, and poorer preservation in the lower horizons due to leaching processes. This level of preservation is reflected in the sediments

sampled at Shovel Down, where any organic material present is in advanced stages of decomposition. For sites such as Wandlebury and Shovel Down, it must be remembered that there is a great deal of sediment variability, especially with regards to areas of gleying versus more oxidised sediments at Shovel Down. With this in mind, it is important to remember to use the information from the CDB with caution, keeping in mind that it is adventurous to use one or two sediment samples to predict the level of preservation of an entire site in such heterogenous sediments as stagnopodzols and rendzinas at Shovel Down and Wandlebury, respectively. The site at Sutton Common is more complex, with clear evidence of leaching and podzolisation as well as groundwater influences (Chapman and Cheetham 2002; Parker Pearson and Sydes 1997; Van de Noort *et al.* 2001). Although past investigations have revealed excellent preservation, the rapid lowering of the groundwater table via irrigation and water abstraction in the vicinity of the site, along with subsequent leaching processes, have had a detrimental impact on the preservation of the archaeological organic material present at the site (*ibid*) (see section 5.5).

For sites that are influenced by groundwater fluctuations, rapid and slow oxidation do appear to have different effects on the preservation of organic material present within these soil environments. The introduction of oxygen into an anaerobic (or waterlogged) environment, by whatever method, is generally detrimental to organic material. The rapid lowering of the groundwater table, at sites such as Over, can result in advection, where dissolved chemicals are rapidly carried away in the groundwater; the rapid loss of moisture and fine material (e.g. organics and clay), and leaching of soil nutrients, exposes any organic material to highly detrimental oxidising conditions (Welch and Thomas 1998). However, the natural fluctuations of the groundwater table and the slow oxidation of the soils, at sites such as Savernake, often result in diffusion (*ibid*). Unlike advection, diffusion is a slow process, which transports soil chemicals and nutrients from high concentrations to low concentrations within the soil profile (*ibid*). Given that diffusion is slow, there is less likely to be significant damage to the organic material in the short term, although prolonged exposure to these conditions could prove as detrimental as rapid oxidising conditions (*ibid*).

In the case of iron oxide deposition, the repeated fluctuation of the groundwater table can result in either iron replacement or iron panning. While iron replacement can preserve the structure of the organic material, thereby providing valuable information in the form of pseudomorphs, panning can form a protective barrier around organic remains, effectively acting as an airtight container, providing ideal preservation conditions. The presence of iron

pans in burial mounds in Denmark and their preservation attributes are well documented (Breuning-Madsen and Holst 1992, 1998; Breuning-Madsen *et al.* 2001; Breuning-Madsen *et al.* 2003; Breuning-Madsen *et al.* 2000; Holst *et al.* 2001), and are ideal examples of the beneficial preservation conditions for archaeological organic remains (see chapter two). In addition, the presence of iron pans lining the features at Over Site 9 (see section 5.2) provided a protective barrier against leaching, which might otherwise have been caused by the rapid lowering of the groundwater table. It is likely that the iron pans developed during the natural fluctuations of the groundwater table when it was 1.2m to 1.5m below the surface prior to gravel extraction, when the groundwater table was rapidly lowered to *c.* 5m below the surface.

Savernake generally had good preservation of organic material, including the presence of celled plant remains, and at Marcham-Frilford, which was the archaeological site used to test the results of the Savernake CDB site, similar preservation conditions were present. Like Savernake, Marcham-Frilford was influenced by the natural fluctuations of the groundwater table and slow oxidation, and the preservation of organic material was very good in both the waterlogged zone and within the fluctuation zone (cf. Kenward and Hall 2000, 522), although there was some decomposition in the latter. Wood, bone and plant remains were recovered from the site, and although the calcareous burial environment also influenced the good preservation conditions (as opposed to the acidic conditions at Savernake), the predominance of iron staining at the site reflected slow oxidation processes.

The results from both the experimental and archaeological sites indicate that the pattern of iron oxide deposition reflects the hydrological/oxidation environment, with the predominance of iron staining indicating slow oxidation and the predominance of iron nodules indicating rapid oxidation. In addition, the level of preservation of organic material is influenced by the rate of oxidation, with rapid oxidation being more detrimental to organic preservation than slow oxidation (Kenward and Hall 2000, 522; Welch and Thomas 1998). However, while this appears to be the case for the sites investigated during the course of this research, it cannot be denied that the process, by which this oxidation occurs, has significant effects on the organic remains. For example, the rapid lowering of the groundwater table causes the translocation of soil nutrients and fine material (organics and clay) from the soil, unless protected by iron panning or iron replacement, as is the case with the Over CDB site and Over Site 9, respectively.

6.3 PRACTICAL APPLICATION OF THE CDB

The practical application of the CDB for future use as part of the planning and conservation process for archaeologists in Britain, needs to be economically viable and straightforward to use. While the bulk analyses provide quantitative information about soil/sediment post-depositional processes, such as leaching, soil micromorphology provides context for these processes as well as a means of identifying the variations in iron oxide deposition. Two pedofeatures have proven most informative: diffuse iron nodules and iron staining, both of which are identifiable through soil micromorphology. As discussed above, the form of iron oxide deposition can provide direct evidence of the hydrological/oxidation environment of the site and can, therefore, help the archaeologist make decisions about the organic preservation potential of the archaeological features and artefacts contained within.

In order to establish a quantitative database of iron nodules present in each horizon or unit, point counting was used to calculate the frequency of iron nodules in six randomly selected $5mm^2$ squares marked out on the surface of the section for each horizon or unit identified, and from this the average was calculated (see chapter three). However, given the amorphous nature of iron staining, a percentage of area covered was recorded by counting the number of $5mm^2$ squares the iron staining filled and calculating the percentage from the total number of squares for the sample (see chapter three). While this method ensured a quantitative analysis, it was extremely time consuming and an alternative method for determining frequency of the iron oxide features is recommended.

The use of FitzPatrick's frequency chart is an alternative method for determining the frequency of a feature based on abundance at known size ranges (Bullock *et al.* 1985; FitzPatrick 1984, 107-114; Stoops 2003). In 2002 I attended an intensive course on soil micromorphology in Ghent, Belgium, which was taught by Professor Georges Stoops. During this course each of us tested the accuracy of FitzPatrick's frequency chart, by first using the charts to estimate the frequency of each of the soil features observed through the microscope, and then used point counting to calculate the actual number for each soil feature. The results were very close with very little difference between the two methods (*c.* 1-2%). Given the ease and accuracy of FitzPatrick's frequency chart, the frequency of iron nodules and iron staining in soils and sediments from archaeological contexts can be calculated in the future using FitzPatrick's chart with confidence that the results, although semi-quantitative, are accurate within 1-2%. In addition, by using the frequency percentages in the chart, the frequency of

iron nodules and iron staining are directly comparable, with further calculations being unnecessary.

The CDB can be utilised by sampling for soil micromorphological analysis, either by coring prior to excavation, or sampling using Kubiëna boxes during excavation. The information from the CDB can be used to ascertain the current level of organic preservation, the redox history of the burial environment, and the potential for long-term preservation given unchanging hydrological conditions. In conjunction with other factors, such as financial considerations and community initiatives, the archaeologist can use the CDB to consider whether the site can be preserved *in situ* and undergo conservation management, or if it would be better for the site to be excavated in order to recover what information has survived to date. Figure 6.1 illustrates three different hypothetical depositional environments typical of archaeological sites in Britain, and how the application of the CDB can be used to suggest possible curatorial action to preserve organic remains. Generally, highly oxidised environments are detrimental to organic preservation and conversely, waterlogged environments are conducive to organic preservation. However, the preservation of organic remains in environments influenced by groundwater fluctuations are more variable, and the CDB can be used effectively to predict organic preservation in these environments. Following this, figure 6.2 illustrates how the CDB can be applied to this type of environment, including the appropriate methodology in the field and the laboratory, and how these results can be used to predict the level of organic preservation in varying hydrological conditions, and the post-depositional processes involved. These hypothetical examples highlight how the CDB can be used as an efficient curatorial tool for making decisions to preserve *in situ,* or to preserve by record via excavation and publication.

Issues of conservation versus rescue excavation continue to be debated (Biddle 1989; Canti *et al.* 2004; Canti and Davis 1999; Caple 2001; Caple and Dungworth 1997; Chapman and Cheetham 2002; Cox *et al.* 1995; Cronyn 1990, 2001; Frankel 1993; French *et al.* 1999; French and Taylor 1985; French 2004; Startin 1993), and will be briefly discussed in the following section.

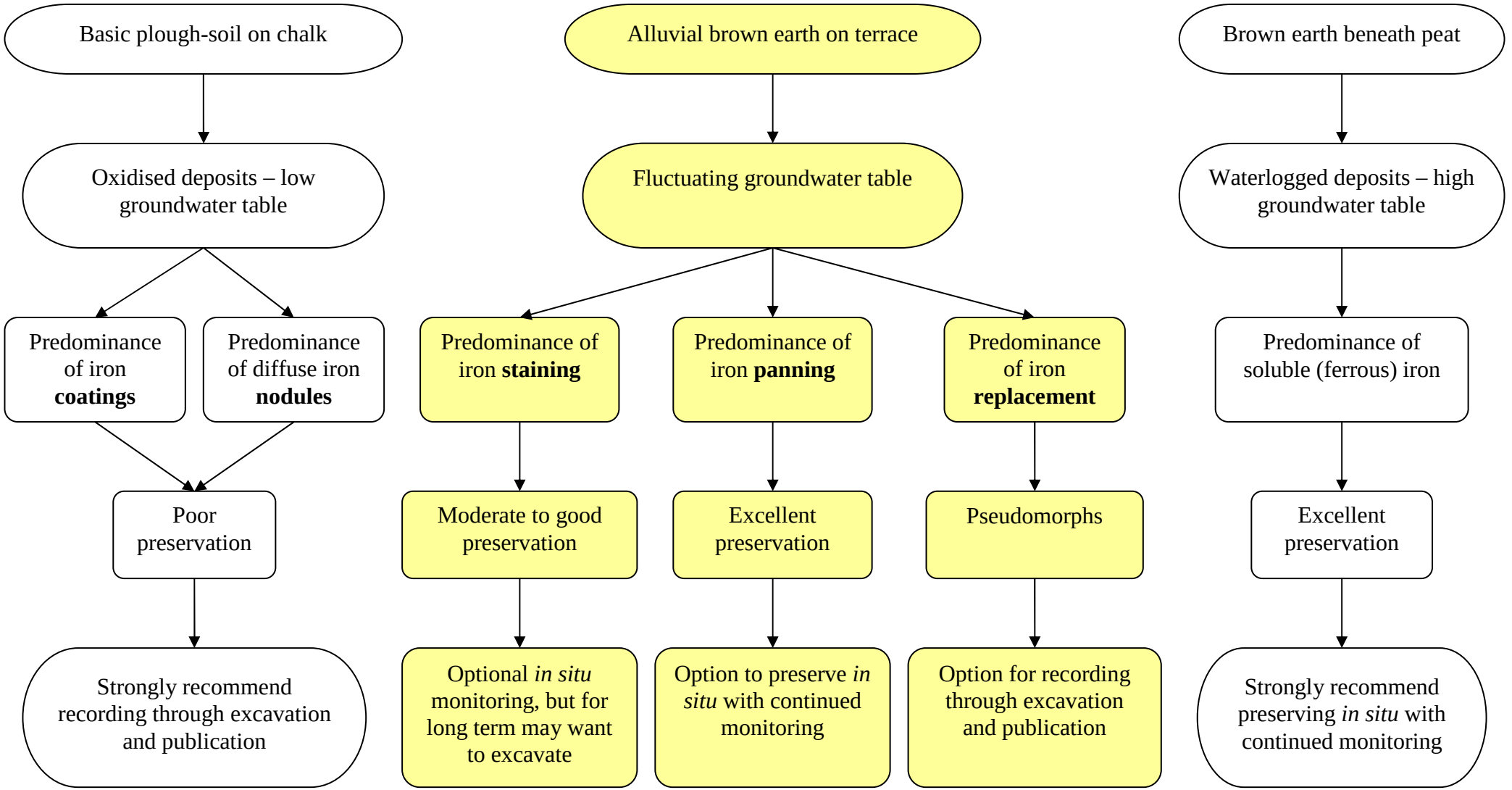


Figure 6.1. Flowchart outlining some environments typical of archaeological deposits in Britain, and the suggested application of the CDB as a curatorial guideline for organic remains.

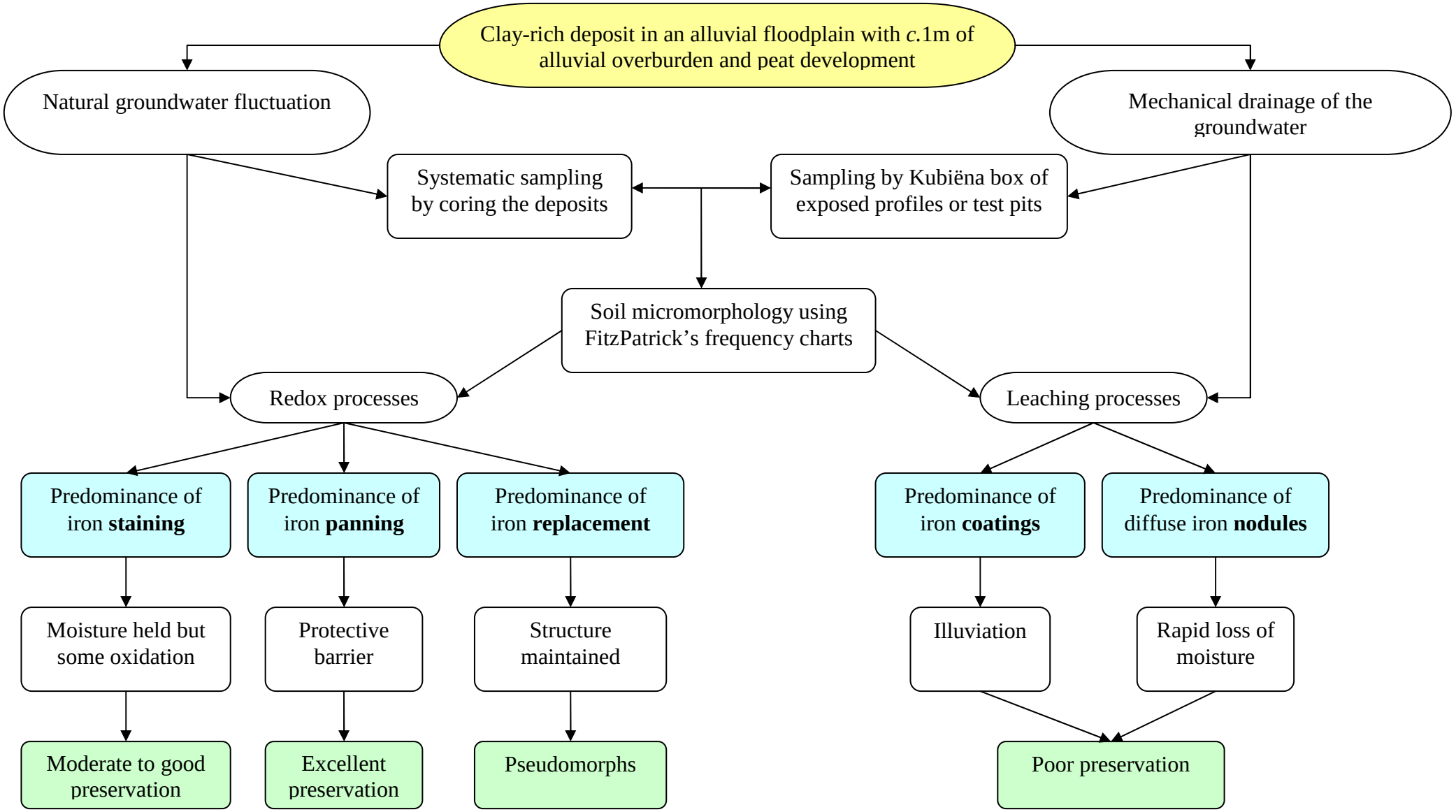


Figure 6.2. Flowchart describing the use of the CDB as a curatorial guideline for deposits influenced by a fluctuating groundwater table, and the predicted level of organic preservation.

6.4 PRESERVATION AND CONSERVATION

In 1990 the Department of Environment published *Planning Policy Guidance 16: Archaeology and Planning*, otherwise known as PPG16, which provides guidelines for planning authorities in England, property owners, developers, archaeologists, amenity societies and the general public (DoE 1990). It outlines the "Secretary of State's policy on archaeological remains on land, and how they should be preserved or recorded both in an urban setting and in the countryside" (*ibid*, paragraph 1). The purpose of PPG16 is to place the onus of responsibility for the preservation of archaeological remains on the developer and local planning authorities who are required to seek assistance from the County Archaeological Officer or equivalent, or English Heritage (*ibid*). The preference of *in situ* preservation of important archaeological remains is strongly recommended by PPG16, and it maintains that:

> Archaeological remains should be seen as a finite and non-renewable resource, in many cases highly fragile and vulnerable to damage and destruction. Appropriate management is therefore essential to ensure that they survive in good condition. In particular, care must be taken to ensure that archaeological remains are not needlessly or thoughtlessly destroyed. They can contain irreplaceable information about our past and the potential for an increase in future knowledge. They are part of our sense of national identity and are valuable both for their own sake and for their role in education, leisure and tourism (*ibid*, paragraph 6).

While there is an understanding that not all archaeological remains are of national and/or international importance, where a development project is necessary, the planning response must include provisions for the *in situ* preservation of archaeological remains (*ibid*). Further, each case must be assessed independently and for those archaeological remains that are deemed less important than the benefits of the development to the community, detailed excavation must be carried out and the remains be preserved by record (*ibid*). However, PPG16 maintains that:

> From the archaeological point of view this should be regarded as a second best option. The science of archaeology is developing rapidly. Excavation means the total destruction of evidence (apart from removable artefacts) from which future techniques could almost certainly extract more information than is currently possible. Excavation is also expensive and time-consuming, and discoveries may have to be evaluated in a hurry against an inadequate research framework. The preservation *in situ* of important archaeological remains is therefore nearly always to be preferred (*ibid*, paragraph 13, but cf. Frankel 1993).

The information gained from the CDB during the course of this research project is a valuable asset when faced with a decision to preserve archaeological remains *in situ* or to record the site through excavation. As discussed above, the soil/geology type and the hydrological/oxidation environment of the site play an important role in preserving the more delicate organic remains in archaeological sites. For instance, if the soil is a podzol or rendzina, then the preservation of the organic remains is going to be poor in the former, and will be biased towards particular types of organic remains in the latter. On the other hand, if the site is influenced by the local groundwater table, the chances for good preservation of organic material improve, depending on the rate of oxidation in the soils/sediments. Any development planned for the site generally means that the groundwater table will need to be artificially altered in some way, and so the maintenance of the saturated zones needs to be investigated. However, there are several problems associated with maintaining an anaerobic environment during and after a development project (Davis *et al.* 2004).

At Over (French *et al.* 1999; 2004) and Flag Fen (Lillie and Cheetham 2002; Pryor *et al.* 1992), a clay bund (impermeable clay barrier) and plastic liner, respectively, were built around the archaeological sites to provide a protective impermeable barrier in which water was pumped to provide a localised high groundwater table in order to establish an anaerobic environment. The initial pumping of the water can be detrimental to the organic remains as oxygen is also added through the pumping process (cf. Caple and Dungworth 1997). In addition, Flag Fen has a system where water is continuously added through sprinklers, which can have adverse effects in the long term as oxygenated water is consistently being introduced into a waterlogged environment (Caple and Dungworth 1997; Kenward and Hall 2000). However, experimental burial mound studies carried out at the Lejre Historisk-Arkæologisk Forsøgscenter in 2004, which investigated the different methods of burial mound construction, have shown that anaerobic conditions can occur within three days in a waterlogged environment (Hart and Lewis 2004, Mads Holst, pers. comm.), and once a stable anaerobic environment is maintained, the decomposition of organic remains cease (Cronyn 1990).

Another method of preserving organic remains *in situ* is to rebury them, although this too has complicated outcomes, the most apparent being the material used for reburial (see Canti and Davis 1999). One of the most publicised projects utilising *in situ* preservation by reburial was that of the Rose Theatre in London where high grade silica sand was used (Biddle 1989; Canti and Davis 1999). However, the use of such material is costly both financially and in terms of

a valuable and scarce resource (Canti and Davis 1999). Further, if other minerals associated with sands are introduced to the burial environment, such as iron and other harmful chemicals, this could have adverse effects on the soil chemistry, altering the preservation conditions and ultimately destabilizing the burial environment (*ibid*). In addition, the archaeologist has to make decisions as to what type of archaeological remains are to be preserved, as some conditions, which may be ideal for organic remains, are corrosive for non-organic remains, such as metal (Cronyn 1990). Hence, the battle for the ideal *in situ* preservation condition continues.

One thing is clear, however: regardless of which method of *in situ* preservation is used, continual monitoring of the burial environment is paramount to ensure the continued conservation of such valuable resources of our past. In sites where the groundwater table plays a major role in the preservation environment of delicate organic remains, the deposition of iron oxide, staining or nodules, can indicate the type of hydrological conditions that are present. The CDB can be used first, to determine the hydrological environment present at a site which may be under threat, and second, to monitor the hydrological environment in the long term to ensure that the burial conditions remain stable.

6.5 PRESERVATION TIMESCALE

Determining the preservation timescale of organic remains in archaeological sites is difficult due to the complexity of the burial environment. Such factors as soil/sediment type play an important role as clay-rich and organic-rich material will be better at holding moisture than more permeable, sandy deposits (Carroll and Oliver 2005). Further, sites that are situated in the fluctuating zone of a naturally fluctuating groundwater table will have variable preservation depending on soil/sediment type (Carroll and Oliver 2005; Kenward and Hall 2000) and the nature of the overburden (i.e. impermeable clay versus permeable sand). Often, organic-rich deposits will "retain water through such short episodes by acting as 'sponges', even when completely out of contact with the watertable *sensu stricto*" (Kenward and Hall 2000, 522). This situation is also true of clay-rich deposits where the impermeable nature of the clay holds moisture 'pockets' within the soil/sediment fabric (Brady and Weil 1999; Limbrey 1975; Rose 2004). Hence, the ability of the deposit to hold moisture will temporarily aid in the preservation of the organic material it contains until the groundwater table rises as part of its natural fluctuation. However, if the groundwater table is mechanically dropped beyond the level of the organic material and remains at the lower level, the loss of moisture

from the deposit will inevitably result in the desiccation of the archaeological organic remains.

At Etton, Cambridgeshire, is an example of a site where dewatering and subsequent desiccation and destruction of the archaeological and palaeoenvironmental records has occurred (French and Taylor 1985). The middle Neolithic causewayed enclosure was under threat from dewatering ahead of gravel extraction in the vicinity of the site, and provided a good opportunity to record the effects of the rapid lowering of the local groundwater table on the preservation of the organic material within the waterlogged deposits of the archaeological site (*ibid*). The site was situated on a calcareous brown earth over First Terrace sands and gravels, and the lower 20-50cm of archaeological deposits, upon discovery, was semi-waterlogged, preserving a rich organic record (*ibid*). The site was capped by *c.* 80-130cm of silty clay to clay alluvium and the area was flooded seasonally until 1953 (*ibid*). The site was monitored before, during and after the groundwater table was lowered and the results showed that the natural fluctuations of the groundwater table did leave the upper deposits subject to oxidation, while the lower deposits were subject to seasonally waterlogged conditions instead of more permanent waterlogging (*ibid*). However, after six weeks of pumping ahead of gravel extraction, the groundwater table was lowered and remained at least 50cm below the deepest archaeological feature, therefore, exposing the organic remains to fully oxidising conditions (*ibid*). This, in turn, affected the preservation of the organic remains in archaeological features at the site, including wood, bone, textiles and pottery, and within a month of the lowering of the groundwater table, desiccation of these remains had taken effect (*ibid*).

The detrimental effects of exposing waterlogged organic remains to oxidising conditions can take place rapidly, and include the disintegration of textiles, cracking, shrinking and crumbling of wood, and the dehydration of bone (Cronyn 1990). Further, uncharred plant remains are highly susceptible to destruction when exposed to oxidising conditions and biological activity (*ibid*). The deterioration of waterlogged organic remains on exposure to oxidising conditions can take place in a matter of seconds or months, depending on the state of the remains and the type of material preserved (*ibid*). It is difficult to predict a timescale for the preservation and/or deterioration of organic material once subjected to oxidising conditions, and it remains a complex issue. However, the deposition of iron oxide in the soil/sediment can occur within days when ferrous iron in reduced deposits is oxidised to ferric iron (Stucki *et al.* 1988), and the pattern of this deposition can reveal how damaging this oxidation is likely to be to organic remains. That is, slow oxidation from a naturally

fluctuating groundwater table (iron staining) can have less detrimental effects on organic remains than the rapid oxidation caused by the mechanical lowering of the groundwater table (iron nodules), and/or excavation (i.e. total exposure to oxidising conditions) of the archaeological site (cf. Cronyn 1990; Frankel 1993; Startin 1993).

6.6 SUMMARY

The need to conserve and preserve archaeological sites as a treasured resource of our past has led to continued and highly debated research in the field. The development of an effective and sensitive tool, which can be used to gauge the preservation of organic material in archaeological sites of varying geology/soil types – the CDB – has armed archaeologists with valuable information for planning and conserving fragile archaeological sites *in situ*. This chapter has discussed the issues involved in preservation and conservation within Britain and has illustrated how the information gleaned from the CDB can be used to assist archaeologists in the planning and protection of valuable sites, which are consistently under threat. The identification of the hydrological/oxidation environment within an archaeological site, through the use of the type of iron oxide deposition present within the soils/sediments, may be an effective means of evaluating the best method for the conservation of a site, whether recording through excavation, or through *in situ* preservation as recommended by PPG16. By comparing the iron oxide features present, the CDB can be used as a tool for monitoring the hydrological/oxidation environment and evaluating the preservation potential of organic remains. It can, therefore, be used as an effective tool for the archaeologists responsible for deciding the curatorial future of sites in Britain.

– 7 –

CONCLUSION TO GAUGING PRESERVATION

The use of iron oxide features, as sensitive indicators of oxidation conditions in soils and sediments, has been applied in this research project to develop a tool for gauging the preservation potential of buried environments in Britain. Given that iron oxide deposition is sensitive to changing oxidation conditions within soils and sediments, four sites with different soil/geology types were subjected to oxidation experiments and a combination of bulk and soil micromorphological analyses. The data were then used to build the comparative database (CDB). Five archaeological sites, with similar soil/geology types to the experiment sites, were selected in order to test the CDB. Sediment samples were collected from various archaeological features, including pits, ditches and buried palaeosols, which were associated with obvious iron oxide deposition identified in the field, i.e. mottling and panning. The patterns of iron oxide deposition reflected the specific oxidation/hydrological conditions currently present in the deposits for each site. Once the existing hydrological/oxidation conditions within the soils and sediments of both the experimental and archaeological sites were identified, the remaining organic material could then be assessed to determine how these conditions affected the preservation of organic material in the buried environment. Hence, the development of the CDB enabled iron oxide deposition to be used to gauge the preservation potential of organic archaeological material on sites of specific soil/geology types within Britain.

Two main hydrological/oxidation environments were identified: sites that were affected by fluctuating groundwater tables, and sites that were not. While the CDB was able to identify the post-depositional processes (e.g. biological activity, translocation and leaching) occurring within the buried environments of the sites which were not affected by fluctuating groundwater tables, it was not able to provide a timescale for the deterioration of organic remains; it was clear, however, that such conditions did not promote organic preservation.

The sites which were influenced by groundwater tables revealed that there is a significant difference in the preservation of organic material in rapid oxidising conditions relative to slow oxidising conditions. Slow oxidising conditions occur as a result of the natural seasonal fluctuations of the groundwater table, whereas rapid oxidising conditions are usually the result of the mechanical lowering of the groundwater table, below the level of the deepest archaeological deposits, usually through drainage activities. It is argued that slow oxidising conditions are less detrimental, in the short term, to organic preservation than rapid oxidation, as clay and organic-rich deposits hold moisture for short periods of time, slowing down the process of desiccation. However, if the groundwater table is permanently lowered, the deposits will be unable to maintain moisture levels and the organic remains contained within these deposits will be rapidly exposed to the process of desiccation and decomposition. The type of soil/sediment plays an important role in maintaining high moisture levels in the deposits. Clays and organic-rich soils/sediments are able to hold more moisture due to their impermeable nature and structure. Clay particles absorb water molecules into their platy structure, resulting in the clay swelling when waterlogged and shrinking when oxidised. Organic material behaves like a sponge, absorbing water through capillary action into the cells, which help to maintain its physical structure. Conversely, more permeable sands have low moisture contents due to the moisture being evaporated and/or drained away from the deposits.

With *in situ* preservation of nationally and internationally important archaeological sites at the forefront of conservation issues in Britain, the CDB is a useful curatorial tool for both identifying existing and past hydrological/oxidation conditions, as well as for monitoring the burial conditions of sites that are currently preserved *in situ*. The CDB can be used as part of the archaeological evaluation process ahead of necessary development to first, identify the organic preservation potential of an archaeological site and subsequently, to monitor the preservation conditions during and after development. It can also aid in decisions regarding the restoration of the original burial environment, such as whether it would be worthwhile to reinstate the original groundwater levels in a once anaerobic site, which can then continue to be monitored for changes in oxidation of the soils/sediments.

While there are many benefits to using the CDB as a tool for gauging the preservation of organic material in archaeological sites, there are some limitations to the scope of the database. For example, the effect of microbial activity on the deposition of iron oxide has not been addressed, as this was outside the scope of this thesis. Instead, the CDB was developed

based on the chemical and physical processes of iron oxidation for which oxidation experiments could be easily designed. In addition, there are many different types of iron oxide minerals, each with specific oxidising environments. The identification of these minerals could provide additional information about the buried environment and subsequently provide a more detailed picture of the preservation potential of an archaeological deposit. Further, the crystal structure of these minerals varies with the rate of oxidation, which could lend support to the observed correlation between oxidation rates and differences in iron oxide deposition patterns identified during the course of this research. This information could be obtained through microprobe and scanning electron microscopy.

Given the limitations outlined above, further work on the identification of specific iron oxide minerals and the effects of microbial activity on iron oxide deposition would be beneficial, and a solid starting point for improving the scope and accuracy of the CDB. For example, the patterns and crystal structure of iron oxide mineral deposition caused by microbial respiration and consumption could be identified, and the rate of oxidation determined. This, in turn, could be used to predict the effects of oxidation rates via microbial activity on the preservation of organic material, and could result in a timeframe for organic decomposition. This timeframe would be invaluable for determining the preservation potential of sites that are not influenced by groundwater table fluctuations, e.g. rendzinas and podzols. In addition, the range of soil/geology types included in the CDB could be extended, expanding the scope of the CDB and improving its accuracy as a tool for gauging preservation. Further, different climatic zones with more complex oxidising conditions could be examined, thereby increasing the range of soil/sediment types to include those that develop in Mediterranean, tropical and sub-tropical environments. By expanding the CDB to include soil/geology types from different parts of the world, the database could become a globally applicable curatorial tool for archaeologists and an invaluable resource for cultural resource planning and management policies worldwide.

– APPENDIX A –

This appendix includes two tables. Table A-1 presents other authors' research on redox processes and the effects these processes have on the preservation of archaeological sites. Table A-2 presents the different types of iron identified through the literature, their magnetic nature, and the environment in which they are likely to be found.

Table A-1. This table summarises four of the sites in Britain which have undergone groundwater monitoring in order to assess the effects of redox processes on the preservation of archaeological sites.

Site and References	Archaeology	Monitoring Method	Groundwater Manipulation	Effects on Archaeology
Sutton Common (Caple and Dungworth 1997; Chapman and Cheetham 2002; Parker Pearson and Sydes 1997; Van de Noort *et al.* 2001)	Iron Age enclosures and palaeochannel	Placement of 50 piezometers across the site and mapping of the groundwater via GIS; redox potential and monitoring of soil microbial activity	Lowering of the groundwater due to arable cultivation, irrigation and water abstraction in the vicinity	Significant reduction in the quality of organic preservation, the loss of identifiable cut-marks in the wooden remains and the general **desiccation of organic remains**
Flag Fen (Lillie and Cheetham 2002; Pryor *et al.* 1992)	A series of Bronze Age man-made wooden avenues/ causeways	Placement of piezometers at various locations and depths across the site	Lowering of the groundwater due to drainage works in the vicinity	Serious threat to waterlogged organic remains, and **desiccation of a series of wooden avenues/causeways**
Etton (French and Taylor 1985)	Neolithic causewayed enclosure	Monitoring points at 20m intervals running from south to north at the western edge of the enclosure	Dewatering of site due to water abstraction ahead of gravel extraction in the vicinity	Water table dropped 1m below the deepest parts of the normally waterlogged enclosure resulting in **desiccation of the organic remains**
Over (French *et al.* 1999; French 2004)	Bronze Age barrow mounds, enclosures and field systems	Hydrological monitoring since 1994; water quality assessment and archaeological excavation	Dewatering of site due to water abstraction ahead of gravel extraction in the vicinity	Water table dropped to 5m below the ground surface and well below previously waterlogged archaeology resulting in **desiccation of organic remains**

Table A-2. This table summarises the soil environment and magnetic susceptibility of different types of iron oxide minerals found in soils. (Information for this table has been collected from Kapička and Petrovský 2003; Loeppert and Inskeep 1996; Stucki *et al.* 1988).

Iron Mineral	**Soil Conditions**	**pH**	**Magnetic Susceptibility ($x10^{-8}$ (m^3/kg^{-1}))**
Goethite ($\alpha FeOOH$)	Well oxidised or arid or semi arid environment	Acidic	70
Hematite (αFe_2O_3)	Well oxidised or arid or semi arid environment	Alkaline	40
Lepidocrocite ($\gamma FeOOH$)	Hydromorphic soil - temperate and sub-tropical; requires **redox processes**	Acidic	70
Maghemite (γFe_2O_3)	Sub-tropical and tropical soils; also burning up to 300-500ºC	Neutral to alkaline	26000
Magnetite (Fe_3O_4)	Sub-tropical and tropical soils; also burning up to 300-500ºC. Can transform to maghemite via fire in warmer climates only.	Neutral to alkaline	56500
Ferrihydrite ($5Fe_2O_3 \cdot 9H_2O$)	Forms in most soils in minor quantities but a major component of **fluctuating redox environments**; forms in presence of organics, often as a result of rapid oxidation	Neutral to alkaline = chemical oxidation; acidic = microbial oxidation	40

– APPENDIX B –

CALIBRATION OF THE TDR 300 MOISTURE METER

The TDR 300 measures the volumetric water content (VWC) of the soil based on the bulk permittivity properties of soil. The VWC is "the ratio of the volume of water in a given volume of soil to the total soil volume. At saturation, the volumetric water content (expressed as a percentage) will equal the percent pore space of the soil" (Spectrum Technologies 2003, 10). The meter's 20cm probes are pushed into the soil surface. Then,

> The electronics embedded in the probe body send a wave down the rods. This signal travels the length of the rods and is partially reflected when it reaches the interface between the rod tips and the soil. This signal is transformed into a square wave output with a frequency proportional to volumetric water content. The measurement volume is an elliptical cylinder extending, radially, 3cm from the rods with a height equal to the length of the rods (20cm). The measured volumetric water content is the average over this entire volume (Spectrum Technologies 2003, 10).

In order to calibrate the TDR 300 moisture meter two experiments were carried out in the Geography Department. Nine litres of "dry", moderately sorted, medium-size sand (determined by PSD) were placed into a bucket and moisture readings taken with 10 repetitions. The level of moisture was gradually increased in 5% increments with moisture readings taken at each increase in moisture. That is, 450 ml of deionised water were added using a mister (e.g. bottle used was Mr Muscle spray bottle). This was to obtain maximum mixing of liquid and solid. Once each 450ml was added the sand was mixed by pouring the sand from one bucket into another and repeated three times. The deionised water was added until the sand reached its saturation point of 35% moisture. In addition, small samples were taken at each increasing increment of moisture to be analysed using LOI. These samples were weighed, heated to 105ºC for 3 hours and weighed again. The percentage of moisture loss was then calculated using the following formula:

$$\frac{\text{weight before } 105ºC - \text{weight after } 105ºC}{\text{weight before } 105ºC * 100}$$

The TDR 300 was also tested in 100% water using both tap water and deionised water. The two different types of water were used to ensure that the moisture meter was not relying on electrical conductivity to measure moisture. Both water types gave similar readings.

The results of the experiments were statistically analysed using *SPSS* 13.0. There was a significant relationship between the percentage of water detected by the TDR300 and the percentage of water determined by LOI, r = .981, *p* (two-tailed) <.01. This would suggest that the TDR300 was calibrated, and therefore, the in-field moisture readings taken by this meter are valid indications of actual soil moisture content.

– APPENDIX C –

ACETONE REPLACEMENT, IMPREGNATION AND THIN-SECTIONING PROCESS

ACETONE REPLACEMENT

It was necessary to treat the proxy group of samples from each site in a way that would not alter their original or in-field state, thereby reducing any changes that may occur during the removal of moisture from the soil. As noted by MacLeod (1997), the best way to remove moisture from samples prior to impregnation with a resin mix is to use acetone replacement. This method enables moisture to be removed from the sample without introducing oxygen and it is, therefore, ideal for protecting the original soil structure and its chemical and/or biological condition.

Acetone replacement can be done by two main methods: an acetone bath or acetone vapour replacement. An acetone bath requires the samples to be completely submerged in acetone and is particularly good for waterlogged sediments, such as samples taken from a lake. Acetone vapour replacement is used for wet, but not necessarily waterlogged, samples and was the preferred option for this research.

Four large Tupperware cake boxes were used. Cake airing racks were cut to size and placed on top of empty Kubiëna frames inside the cake boxes. The samples were then placed on the cake racks and a mud-map of the placement of the samples was drawn in my laboratory notebook. In addition, the lids and sides of the cake boxes were labelled with the positions of the samples. Acetone was siphoned into the cake boxes until the level of acetone reached half way up the side of the empty Kubiëna frames. The lids of the cake boxes were then sealed and the date was recorded on the cake boxes. The samples were left for no more than one day.

Table C-1. Calibration table for acetone vapour replacement, taken from MacLeod (1997, 5).

% water in acetone v/v	% water in acetone w/w	sp. gravity at 18ºC	sp. gravity at 20ºC	sp. gravity at 22ºC
0	0	0.793	0.791	0.79
1	1.26	0.796	0.795	0.793
2	2.52	0.8	0.798	0.796
3	3.76	0.803	0.802	0.8
4	5.01	0.807	0.806	0.803
5	6.24	0.81	0.809	0.806
6	7.46	0.814	0.813	0.81
7	8.68	0.818	0.817	0.8135
8	9.9	0.8215	0.82	0.817
9	11.11	0.8255	0.824	0.82
10	12.32	0.828	0.827	0.823

Following the experiments carried out by MacLeod (*ibid*), a small volume of "wet" acetone was siphoned from the cake boxes into a glass cylinder, the temperature was recorded using a standard glass thermometer, and a 0.790 – 0.800 hydrometer was placed in the cylinder to measure the specific gravity. This was recorded and compared to the standard calibration table in MacLeod (*ibid*) to determine the percentage of water still remaining from the acetone vapour replacement (table C-1). The remaining "wet" acetone was siphoned from the cake boxes into an empty drum for disposal. Fresh acetone was then siphoned into the cake boxes, the lids were sealed and the date and percentage of water remaining were recorded on the lids. This procedure was repeated until the amount of moisture measured was less than or equal to 0.5% and the samples were ready for impregnation.

IMPREGNATION

Following drying or acetone replacement, the samples were placed into large ice-cream containers and impregnated with resin mix. Two different resin mixes were used depending on the soil type to be impregnated. The first, a general recipe recommended by the McBurney Laboratory, was 1500ml of unsaturated crystic polyester resin (17449), 500ml of acetone, 30ml of catalyst MEKP (methyl ethyl ketone peroxide) and 1ml of crystic accelerator G. The second recipe, a variant on the first, was designed for more clay-rich soils and had an increased amount of acetone: 1000ml resin, 1000ml acetone, 30ml MEKP and 1ml accelerator G. Each ingredient was mixed in turn and then poured into the containers, with care not to

disturb the soil samples. The containers were then placed into the vacuum chamber for 24 hours at 20 psi, at which point the samples were topped up with their respective mixes and placed back into the vacuum chamber at 20 psi for a further 24 hours. The containers were then removed from the vacuum chamber and placed into storage fume cupboards to cure. The curing process took from 6 to 12 weeks, at which point the resin had hardened and the containers were placed in the oven at 25ºC overnight in preparation for cutting.

THIN-SECTIONING PROCESS

The hardened blocks were cut using a disc bladed saw (an MK Diamond Tile and Brick Saw) to remove the exterior surface of the block and expose a fresh surface. A slice 5mm in thickness was then cut from the fresh surface, providing a flat section. The section was then temporarily mounted on prepared glass and an A. G. Brôt micrometric advance grinder/polisher was used for an initial grinding in order to prepare the slice for a permanent mount to a glass slide. Two grinding wheels were used: a coarse wheel that ground the slice down to 4mm thick; and a fine wheel that ensured that the surface of the slice was smooth and flat, with as few marks as possible, providing a clean finish. After drying and removal of excess oil resulting from the initial grind, the prepared side of the slice was glued onto a 3mm prepared glass slide using an altered resin mix of 20ml resin, 0.8ml MEKP and 0.7ml of accelerator G. The samples were then clamped in a geologic-rock-sample press to ensure constant pressure for approximately 12 hours. The samples were returned to the Brôt for further grinding, first with the coarse wheel to remove the bulk of the section, then with the fine wheel to finish the section to 25-30µm. The section was then finished by hand polishing where necessary. The final process was to cover the section by placing a thin slip of glass over it. The resin mix used for the permanent mount was also used to bond the glass slip to the section.

– APPENDIX D –

BULK ANALYSES PROTOCOLS FROM THE DEPARTMENT OF GEOGRAPHY, UNIVERSITY OF CAMBRIDGE

All the protocols described here are taken directly from the Department of Geography website and remain unaltered. The website URL is:

http://www-labs.geog.cam.ac.uk/protocols/

PARTICLE SIZE ANALYSIS - MALVERN MASTERSIZER PROTOCOL (V. 1-2)

The Malvern Mastersizer X is a laser particle sizer used to measure the particle size distribution of soils and sediments. It has a variety of lenses which can measure particles ranging from 2mm to 0.1µm. The Mastersizer is connected to a personal computer, on which the particle size data can be displayed in both table and graph form. The data can also be exported to a spreadsheet for more sophisticated analyses.

- 50ml plastic tubes should be used; they should be clean and numbered with permanent marker.
- A lump of sediment approx. 1-5g is put in the bottom of the tube. If samples have been processed for magnetic susceptibility then this sample is used for particle size analysis.
- Each tube is topped up with 4.4% sodium pyrophosphate (wear gloves and glasses when handling) and put in a water bath at 90ºC for approximately three hours, stirring once with a glass rod.
- The samples are removed from the water bath and centrifuged at 3500 rpm for 13 minutes. It is important to use the scales to balance the tubes, topping up with water if necessary.
- The tubes are then removed from the centrifuge and the liquid decanted off.
- Samples are now ready for the Malvern.

Switch on the power, check the drain tubes are in the sink and switch on the water supply (tap). Open the Mastersizer software on the PC. Samples are run twice with two different lenses - 45 and 1000µm to get a full range of particle sizes. Before starting it is important to check which lens is being used, and that the software recognises this. Go to the Setup menu, then hardware, and adjust the lens range as appropriate.

Switch on the sample suspension unit, and put the cell stir, ultrasonic stir and sample pump on at about 75%. Using the fill and drain switches on the front of the sample unit, fill the bath approximately two-thirds full with water. On the software either click the Go button with the mouse, or more usually when using the monitor and keyboard next to the Malvern, press Shift Alt 2, and a window will come up where you enter the sample name. In the notes section it is useful to put the lens size i.e. 45 or 1000. Then press enter. The Malvern then automatically checks the water in the bath, moves the laser and so on. When this is complete it will have a background reading of the obscuration value of clean tap water. If this is below 1% it is now OK to add the sample.

Before adding the sample, mix it on the whirlimixer. It is important to ensure the entire sample is moving freely within the tube and that there are no lumps of clay stuck to the bottom of the tube. A few drops of the sample should be added to the bath straight from the whirlimixer so all the particles are evenly mixed and distributed. Check the obscuration value given on the screen. An ideal value is 15%, between 10 - 20% is acceptable. If the value is too low, add another drop or two of sample, if it is too high add more water using the fill switch to dilute the sample. When the value is correct hit the space bar and the analysis will proceed. When this has finished and the graph is plotted drain the sample away. Rinse the bath and tubes three times to flush the sample away, ensuring that no particles are left on the inside of the bath. You are now ready for the next sample.

All samples should be run for 45µm, then 1000µm. The data is automatically saved during analysis. At the end it is necessary to combine the two sets of data to produce one record for each sample. This is done by opening a new Excel file. Then in the Mastersizer programme go to the Control menu and choose the run programme option, then load ‘blend.bsc’. Enter the filenames which contain the data, sample numbers and so on, then a statistical summary will be sent to the Excel file. The data in the Excel file can then be manipulated and plotted in Psimpoll.

LOSS-ON-IGNITION PROTOCOL (V. 1.2)

This technique may be used to measure % water, bulk density, % organic, % calcium carbonate and % silicate residue in a variety of soils and sediments. The 105°C oven is used to dry the samples, while the muffle furnace is employed at 500°C and 950°C to remove organic matter and break down carbonate respectively. Electronic balances (2 and 3 dp) are routinely used to determine the loss in mass at various stages of the analysis. However, analytical balances are available for work with very small samples.

Equipment

- Balance - 2 or 3 decimal place, e.g. in 1g, 10% accuracy = 0.1g, 1% accuracy = 0.01g, 0.1% accuracy = 0.001g
- Crucibles of an appropriate size for the samples - differently numbered
- Desiccator - with purple silica gel, if white put in 105ºC oven for 6 hours to dry out.
- Drying oven - Must be booked in advance!
- Heat proof gloves.
- Muffle Furnace - capable of up to 1000ºC - Must be booked in advance!
- Tongs.
- Trays & stack - capable of withstanding 1000ºC.
- Volumetric Sampler.
- If you have large batches of samples, using a Sartorius balance connected to a pc is a useful way to speed up collection of data.

Protocol (%water, bulk density, %organic, %calcium carbonate, %silicate residue)

- Clean, dry, numbered porcelain crucibles are weighed empty.
- Approximately 1g of wet sediment is placed in the crucible, and the wet weight recorded. If bulk density of the sample is required a calibrated $1cm^3$ brass volumetric sampler should be used and the sample should be weighed, allowing mass per unit volume to be calculated.
- Crucibles should then be placed on trays, the tray rack may be required if large numbers of samples are being processed.
- The samples are dried for 6 hours (until constant weight is achieved) usually overnight at 105ºC in either the Drying Oven or Muffle Furnace. Remove trays carefully using the heat proof gloves. Use tongs to place crucibles in desiccator until they reach a temperature at which they can be handled safely. The desiccator prevents the

absorption of water from the atmosphere, and therefore, weight gain. Then weigh samples again.

- The samples are transferred to a muffle furnace then heated to 550ºC for at least six hours (overnight), the furnace should then be reduced to ~100ºC, when this temperature has been reached samples should be allowed to cool in a desiccator to a temperature at which they can be safely handled, then weighed.
- The samples are then returned to the furnace and heated to 950ºC for at least six hours (overnight) the furnace should then be reduced to ~100ºC, when this temperature has been reached samples should be allowed to cool in a desiccator to a temperature at which they can be safely handled, then weighed.

Results

- The weight loss when the samples are dried at 105ºC (wet weight - dry weight) represents of the amount of pore-water held within the sample. The percentage of water should be expressed as a proportion of the wet weight. If the volume of the sample taken is known then the "Bulk Density" can be calculated from this, expressed as weight of sample per unit volume, e.g. g/cm^3 ($g\ cm^{-3}$).
- The weight loss between 105ºC and 550ºC as a percentage of the total original dry sample weight is the % organic material. This probably also includes water loss from clay minerals, this is likely to be an insignificant addition.
- The weight loss between 550ºC and 950ºC is representative of the amount of CO_2 released from the sample. This can be used to calculate the amount of $CaCO_3$ present in the sample by using the ratio between the molecular weights, expressed as a percentage of the total original dry sample weight, this is the % carbon.

Calculation (molecular weights in brackets)

- Ca (40.08) + C (12.01) + O_3 (3 x 16.00) = $CaCO_3$ (100.09)
- C (12.01) + O_2 (2 x 16.00) = CO_2 (44.01) Removed between 550 - 950ºC
- Ca (40.08) + O (16.00) = CaO (56.08) Remains in sample
- So to calculate the quantity of $CaCO_3$ the weight of CO_2 lost must be multiplied by a factor to account for the CaO remaining in the sample.
- $CaCO_3$ (100.09) / CO_2 (44.01) = 2.274
- So the part of the sample that is represented by the CaO is 2.274 times that of the known CO_2.

- So to calculate the quantity of $CaCO_3$ in a sample the weight lost between 550 - 950ºC must be multiplied by 2.274.
- The weight of the residue remaining after 950ºC, minus the adjustment for carbon, as a percentage of the total original dry sample weight is expressed as the % silicate residue.

% Charcoal

- When analysing samples for % charcoal, a slightly different method is used. The samples are prepared as above, and dried at 105ºC, but then heated to 400ºC and 480ºC instead of 550ºC and 950ºC. This distinguishes between organic matter, and charcoal.

MAGNETIC SUSCEPTIBILITY PROTOCOL (V. 1-1)

The Bartington Magnetic Susceptibility Meter is used to measure the magnetic susceptibility of a variety of soils and sediments. Magnetic susceptibility depends on the amount, type and particle size of the ferro-magnetic minerals present. The meter may be used with a scanning loop to measure cores of sediment, or with a well-type sensor for discrete samples.

Equipment

- Bartington magnetic susceptibility meter.
- Either, pot (discrete sample) coil or a (core) reader attachment.
- Plastic pots and lids (if using discrete samples).
- Recording sheet appropriate to method.
- Booked bench space to use the equipment in!

Preparation of Discrete Samples

- Sediment samples are put into 10 cm^3 plastic pots so that the pot is full to the top, and weighed. An average weight of empty pots is taken to subtract from the full pot weight. The pots are labelled with permanent marker pen.
- Samples are put in a drying oven overnight at no higher than 105ºC - take care not to melt the plastic pots!
- The samples are then removed from the oven, the lids fastened on and the dry weights recorded.

- The magnetic susceptibility meter is set up and zeroed, it may take some time for the meter to stabilise so it is worth setting up the machine half an hour before you start taking readings. Any large metal objects such as metal trays, watches or belt buckles should be kept away from the meter.

Analysis of Discrete Samples

The readings are taken as follows:

- The machine beeps at regular intervals (15.01 sec.). At the first beep the sample hole is empty and the value noted (A).
- The sample is then lowered into the hole and the second beep value ignored as this covers the time whilst the pot was being placed into position.
- The third and fourth beep values are recorded (B & C) the sample is then removed.
- The fifth beep is ignored and the sixth beep value recorded (D). The values recorded measure a background magnetic field before and after the sample value.
- The next sample is then measured in the same way.
- When a routine is established there is usually enough time to move samples so that blank value D can become blank value A for the subsequent sample. Taking these two readings allows compensation to be made for natural drift in the earth's magnetic field.
- As a final reading an empty pot is measured.

Calculation

The magnetic susceptibility of a sample is calculated in the following way:

$$\frac{(B+C)/2 - (A+D)/2}{\text{dry weight of sample}}$$

- This gives the magnetic susceptibility of the sample in SI units /g dry weight.
- Then the magnetic susceptibility value for the empty pot is subtracted to allow for the magnetic properties of the sample pot, to give a final value.

– APPENDIX E –

PROTOCOL FOR PH, EC AND REDOX

I wrote this protocol for the benefit of the McBurney Laboratory members and made it available on the McBurney shared space on the PWF at the University of Cambridge.

PREPARATION OF SAMPLES

1. First dry your samples either on the shelves provided or in an oven at a low, constant temperature (e.g. 30°C).
2. Sieve your samples through a 2mm sieve and grind with a mortar and pestle to a fine sediment.
3. You will need approximately 30ml of sediment in order to do three repeats for each sample.[2]
4. Be sure to clean the mortar and pestle with deionised water between samples.[3]
5. You may wish to draw up a table in *Microsoft® Excel*, for example, to record your readings, with three columns for each measurement to accommodate the three repeats for each sample.
6. Calibrate the meters following the instructions below.
7. Be sure to rinse each of the plastic 50ml beakers with deionised water before beginning.
8. Fill one or two (as needed) 100ml beakers to *c.*80ml with deionised water for each of the meters.
9. Pour 10ml of the same sample into three 50ml beakers (30ml of sample in total).

[2] Taking three readings for each sample (n=3) is scientifically accepted practice to obtain an average reading for the sample.

[3] See either Julie Miller (jb10001@cam.ac.uk) or Charly French (caif2@cam.ac.uk) to get access to the deionised water in the George Pitt-Rivers Laboratory.

10. Top up each beaker with deionised water to 50ml. This is a 1:5 solution.[4]
11. You may wish to do three samples at one time i.e. nine 50ml beakers.
12. Stir, using a glass rod, each beaker for approximately 30 seconds to ensure the solution is mixed through.[5]
13. Be sure to rinse the glass rod with deionised water between samples to prevent cross-contamination.[6]
14. Follow the instructions below to measure your samples. It is up to you how far you immerse the probes, (e.g. if you rest it on the bottom of the beaker or place it in half way) as long as the probes are fully immersed and you are consistent with your method.
15. Rinse the probes between samples with deionised water to prevent cross-contamination.
16. Place the meters in the 100ml beakers of deionised water in between samples as this will help rinse them. Be sure to replace the water when it becomes dirty.
17. When disposing of used samples wash out the beakers in the sink (with a sediment trap) using tap water, and be sure to give them a final rinse using deionised water.
18. Dry the beakers and, if required, repeat steps 9 to 18.

OPERATION INSTRUCTIONS FOR THE PH/EC METER

1. Remove the protective cap.
2. Press and hold the ⏻ /MODE button for 2-3 seconds. All the used segments on the LCD will be visible for a few seconds, followed by a percent indication of the remaining battery life (e.g. %100 BATT).
3. Set the **pH** mode by pressing the SET/HOLD button.
4. Submerge the electrode in the solution to be tested.
5. The measurements should be taken when the stability symbol ◷ on the top left of the LCD disappears.
6. The **pH** value, automatically compensated for temperature, is shown on the primary LCD, while the secondary LCD shows the temperature of the sample.

[4] It is entirely up to you which ratio you use as long as you are consistent with all your samples.

[5] Again it is up to you whether you stir the sediment while taking measurements or give them one stir at the beginning and then take the measurement. You must be consistent with your method.

[6] Use a squirt bottle of deionised water and a container marked "waste: soil + D.I. H_2O" to rinse off the glass rod and meters between samples.

7. To measure **EC**, press the SET/HOLD button until µS is displayed in the top right corner of the LCD.[7]
8. The measurement should be taken when the stability symbol ◷ on the top left of the LCD disappears.
9. The **EC** value, automatically compensated for temperature, is shown on the primary LCD, while the secondary LCD shows the temperature of the sample.
10. When not in use remember to turn the meter off to conserve battery power.
11. Rinse the electrode with tap water to minimise contamination and replace the cap.
12. **Do not use distilled or deionised water for storage purposes.**

pH CALIBRATION[8]

1. Rinse three[9] beakers with deionised water, dry, and pour enough of each buffer solution into a beaker (one for pH 4.01, one for pH 7.01 and one for pH 10.01) so as to sufficiently immerse the probes.
2. Remove the protective cap from the meter.
3. Press and hold the ⏻ /MODE button for 2-3 seconds. All the used segments on the LCD will be visible for a few seconds, followed by a percent indication of the remaining battery life (e.g. %100 BATT).
4. Set the **pH** mode with the SET/HOLD button.
5. From measurement mode, press and hold the ⏻ /MODE button until TEMP and the current temperature unit are displayed on the lower LCD (e.g. TEMP °C).
6. Press the ⏻ /MODE button again to show the current buffer set: pH 7.01 BUFF (4.01/7.01/10.01 calibration) or pH 6.86 BUFF (NIST 4.01/6.89/9.18 calibration).
7. Press the SET/HOLD button to change the buffer value to pH 7.01 BUFF.
8. Press the ⏻ /MODE button to return to the normal measuring mode.
9. From measurement mode, press and hold the ⏻ /MODE button until CAL is displayed on the lower LCD. Release the button.
10. The LCD will display pH 7.01 USE. The CAL tag blinks on the LCD.

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[7] µS will appear if using a micro-siemens meter. If using a milli-siemens meter then mS will be displayed. Unless you have highly organic sediment (e.g. peat), it is recommended you use a µS meter.

[8] I recommend calibrating the meter between users, if they haven't been used for a while, or when you think the results are erroneous. Use your own judgement.

[9] One beaker is sufficient if using a single-point calibration but you may wish to test the meter with all three buffer solutions – see below.

11. For a single-point calibration, place the electrode in any buffer from the selected buffer set (e.g. pH 7.01 or pH 4.01 or pH 10.01). The meter will recognise the buffer value automatically.
12. If using pH 4.01 or pH 10.01, the meter will display OK for 1 second and then return to normal measuring mode.
13. If using pH 7.01, after recognition of the buffer the meter will ask for pH 4.01 as a second calibration point. Press the ⏻ /MODE button to return to measurement mode or, if desired, proceed with the 2-point calibration.[10]
14. For a two-point calibration, place the electrode in pH 7.01 buffer solution. The meter will recognise the buffer value and then display pH 4.01 USE.
15. Rinse the electrode thoroughly to eliminate cross-contamination.
16. Place the electrode in the second buffer value (pH4.01 or pH 10.01).
17. When the second buffer is recognised, the LCD will display OK for 1 second and the meter will return to the normal measuring mode.
18. The CAL symbol on the LCD means that the meter is calibrated.

EC CALIBRATION

1. Set the **EC** mode by pressing the SET/HOLD button until µS (or mS) is displayed in the top right corner of the LCD.
2. From measurement mode, press and hold the ⏻ /MODE button until CAL is displayed on the lower LCD.
3. Release the button and immerse the probe in the proper calibration solution: HI7031 (1413 µS/cm) for the µS meter and HI7030 (12.88 mS/cm) for the mS meter.[11]
4. Once the calibration has been automatically performed, the LCD will display OK for 1 second and the meter will return to normal measurement mode.
5. The CAL symbol on the LCD means that the meter is calibrated.

[10] It is easiest to use a single point calibration using pH 4.01 or pH 10.01. If you want to confirm the accuracy of the meter then test it by taking readings in each of the buffer solutions being sure to rinse thoroughly between each solution.

[11] These solutions can be borrowed from Dept of Geography – contact Chris Rolfe (cjr46@hermes.cam.ac.uk) or Steve Boreham (sb139@cam.ac.uk).

OPERATION INSTRUCTIONS FOR THE REDOX METER

1. Remove the protective cap.
2. Turn the meter on with the ON/OFF switch located on the top of the meter.
3. Immerse it in the solution to be tested without exceeding the maximum immersion level (noted on the back of the meter).
4. Stir gently and wait for the reading to stabilise.
5. After use, rinse the electrode with tap water to minimise contamination.
6. Remember to turn the meter off when not in use so as to conserve the battery.
7. Always replace the protective cap after use.
8. **Do not use distilled or deionised water for storage purposes.**

REDOX CALIBRATION[12]

1. Check the meter by immersing it in HI7020 ORP solution.
2. The reading should be between 200 and 275 mV at 20°C.
3. If not between this range, clean the platinum tip of the electrode by rubbing it with a soft cotton or lint-free cloth soaked with HI7061 cleaning solution.
4. For more accurate readings, condition the meter by immersing it in a pre-treatment reducing (HI7091) or oxidising (HI7092) solution for half an hour before taking measurements.
5. In case of erroneous readings even after an accurate conditioning and calibration, the reference junction might be contaminated or clogged.
6. Pull out 2mm of the cloth junction to renew the electrode reference (it is recommended to cut the cloth leaving at least 2mm over the reference compartment) and repeat the maintenance and conditioning procedure.
7. The cloth junction can be pulled out approximately 20 times. After that the electrode should be replaced.

[12] This meter should already be calibrated. Check with Julie Miller or Charly French for access to solutions.

– APPENDIX F –

This appendix is a CD which is included in the back of this dissertation. The contents of this CD include the database which was used to analyse the 206 thin sections: 140 for the CDB and 66 thin sections from archaeological contexts. Also included in this CD are the raw data from the bulk analyses performed by the author and the ICP-AES results carried out by ALS Chemex, Canada. The file names are as follows:

ReadMeFirst.pdf	Copyright protection for all data contained in the CD
SMM_CDB.pdf	Soil micromorphology database for CDB sites
SMM_ArchSites.pdf	Soil micromorphology database for archaeology sites
ICP_AES_CDB.pdf	ICP-AES results for CDB sites
ICP_AES_ArchSites.pdf	ICP-AES results for archaeology sites
LOI_CDB.pdf	Loss on ignition results for CDB sites
LOI_ArchSites.pdf	Loss on ignition results for archaeology sites
PSD_CDB.pdf	Particle size distribution results for CDB sites
PSD_ArchSites.pdf	Particle size distribution results for archaeology sites
MS_CDB.pdf	Magnetic susceptibility results for CDB sites
MS_ArchSites.pdf	Magnetic susceptibility results for archaeology sites
pH_EC_Redox_CDB.pdf	pH, EC and redox potential results for CDB sites
pH_EC_Redox_ArchSites.pdf	pH, EC and redox potential results for archaeology sites

– APPENDIX G –

The tables presented here are the results of ICP-AES analysis for each of the four CDB sites and relate directly to the plant nutrient uptake. There are three groups of nutrients on which plants rely: major, macro and micro (Courtney and Trudgill 1976, 63; Trudgill 1977, 25). The major nutrients include carbon (C), hydrogen (H), oxygen (O) and nitrogen (N), which were not measured in the ICP-AES analysis. The macro-nutrients include aluminium (Al), phosphorus (P), sulphur (S), potassium (K), calcium (Ca), iron (Fe) and magnesium (Mg) all of which are included in tables G-1, G-2, G-3 and G-4. Finally, the micro-nutrients include sodium (Na), manganese (Mn), copper (Cu), zinc (Zn), molybdenum (Mo), silica (Si), boron (B), chlorine (Cl) and cobalt (Co), of which silica and chlorine are not included in the ICP-AES results.

Table G-1. The ICP-AES results for the plant nutrients from the samples collected from the Over CDB Site.

Over CDB Site	Plant Macro-Nutrients							Plant Micro-Nutrients						
Sample Name*	Al (ppm)	Ca (ppm)	Fe (ppm)	K (ppm)	Mg (ppm)	P (ppm)	S (ppm)	B (ppm)	Co (ppm)	Cu (ppm)	Mn (ppm)	Mo (ppm)	Na (ppm)	Zn (ppm)
10/03 1.1	4800	1600	21500	600	600	370	<100	<10	5	8	108	1	100	46
10/03 1.2	3400	1100	21500	400	400	370	<100	<10	5	6	88	1	100	41
10/03 1.3	2700	900	19900	300	300	320	<100	<10	4	5	80	1	100	34
10/03 1.4	2800	900	26600	400	300	390	<100	<10	5	6	109	2	100	36
10/03 1.5	2400	700	21500	300	300	370	<100	<10	4	6	78	2	100	33
10/03 1.6	2200	700	23900	300	300	470	<100	<10	4	6	76	1	100	34
10/03 2.1	4200	1400	23100	600	500	410	<100	<10	5	7	111	1	100	44
10/03 2.2	4100	1300	24100	500	500	410	<100	<10	5	7	107	1	100	44
10/03 2.3	3000	1000	20600	400	300	410	<100	<10	4	6	82	2	100	38
10/03 2.4	2700	800	21400	400	300	420	<100	<10	4	6	78	1	100	36
10/03 2.5	2700	800	22900	400	300	430	<100	<10	5	6	85	2	100	37
10/03 2.6	2000	600	24000	300	300	520	<100	<10	4	6	80	1	100	33
01/04 1.1	3500	1200	20500	400	400	330	<100	<10	5	6	70	2	100	40
01/04 1.2	3000	900	20500	400	300	350	<100	<10	4	6	75	1	100	36
01/04 1.3	3100	1000	23500	400	300	480	<100	<10	4	7	87	1	100	38
01/04 1.4	2500	800	22800	300	300	480	<100	<10	4	6	76	1	100	34
01/04 1.5	2100	600	22600	300	300	490	<100	<10	4	6	76	1	100	32
01/04 1.6	2000	500	22500	300	300	470	<100	<10	5	6	75	1	100	32
01/04 2.1	4000	1300	22200	500	500	380	<100	<10	5	9	80	1	100	48
01/04 2.2	2900	800	19400	400	300	310	<100	<10	4	6	68	2	100	35
01/04 2.3	2600	800	21300	400	300	360	<100	<10	4	6	79	1	100	34
01/04 2.4	2400	800	24200	300	300	470	<100	<10	4	6	76	2	100	34

01/04 2.5	2200	800	25800	300	300	580	<100	<10	4	6	85	2	100	33
01/04 2.6	1900	600	22000	300	300	470	<100	<10	5	5	75	1	100	31
04/04 1.1	4300	1400	21800	500	500	390	<100	<10	5	7	83	2	100	45
04/04 1.2	3500	1100	20000	400	400	340	<100	<10	4	7	79	1	100	40
04/04 1.3	3300	1000	23200	400	400	420	<100	<10	4	7	94	2	100	39
04/04 1.4	2800	900	23200	400	300	470	<100	<10	4	7	88	1	100	38
04/04 1.5	2700	900	26700	400	300	540	<100	<10	4	7	93	2	100	37
04/04 1.6	2300	700	24100	300	300	500	<100	<10	4	7	85	1	100	35
04/04 2.1	3800	1200	22000	500	400	380	<100	<10	4	6	83	1	100	43
04/04 2.2	3900	1200	23400	500	400	380	100	<10	5	7	88	1	<100	42
04/04 2.3	3700	1100	27000	400	400	430	100	<10	5	7	106	2	<100	42
04/04 2.4	3300	1000	23600	400	400	420	100	<10	4	6	91	1	<100	39
04/04 2.5	2800	900	25800	400	300	490	100	<10	4	7	96	2	<100	39
04/04 2.6	2200	600	24600	300	300	480	100	<10	4	6	88	1	<100	34
07/04 1.1	6700	2100	24400	800	800	400	200	10	5	10	97	2	<100	50
07/04 1.2	3300	1100	22000	400	400	350	100	<10	4	8	84	1	<100	40
07/04 1.3	3000	1000	22000	400	300	380	100	<10	4	8	83	1	<100	40
07/04 1.4	2900	1000	25100	400	300	490	100	<10	4	9	83	1	<100	42
07/04 1.5	2700	800	23600	400	300	450	<100	<10	4	9	78	1	<100	39
07/04 1.6	2500	800	25000	400	300	590	<100	<10	6	7	85	1	<100	38
07/04 2.1	4800	1500	20900	600	600	330	100	<10	4	7	79	2	<100	44
07/04 2.2	3300	1000	20300	400	400	320	100	<10	4	6	78	1	<100	39
07/04 2.3	3200	1000	22200	400	400	360	100	<10	4	6	85	1	<100	40
07/04 2.4	2800	900	23800	400	300	420	100	<10	5	6	78	1	<100	38
07/04 2.5	2600	800	22600	400	300	420	<100	<10	5	6	75	1	<100	37
07/04 2.6	2300	700	24100	400	300	520	<100	<10	5	6	78	1	<100	37

* Where 10/03 = month/year of collection; 1.1 = oven dried 0-5cm, 1.2 = oven dried 5-10cm etc; 2.1 = air dried 0-5cm, 2.2 = air dried 5-10cm etc

Table G-2. The ICP-AES results for the plant nutrients from the samples collected from the Wandlebury CDB Site.

Wandlebury CDB Site	Plant Macro-Nutrients							Plant Micro-Nutrients						
Sample Name*	Al (ppm)	Ca (ppm)	Fe (ppm)	K (ppm)	Mg (ppm)	P (ppm)	S (ppm)	B (ppm)	Co (ppm)	Cu (ppm)	Mn (ppm)	Mo (ppm)	Na (ppm)	Zn (ppm)
10/03 1.1	9300	103000	19000	900	1500	1290	900	10	6	14	650	1	100	62
10/03 1.2	10300	104500	20300	900	1600	1240	800	10	7	14	687	1	100	64
10/03 1.3	10000	102500	20400	800	1500	1140	700	10	7	14	664	<1	100	61
10/03 1.4	10800	110000	21000	900	1600	1190	800	10	7	16	707	1	100	65
10/03 1.5	10700	115500	20400	900	1600	1210	800	10	6	15	702	1	200	67
10/03 1.6	10200	108000	19700	800	1500	1140	700	10	6	14	666	<1	100	60
10/03 2.1	10100	99900	19400	1000	1600	1360	900	10	6	15	668	1	100	64
10/03 2.2	10100	111500	19600	900	1600	1260	800	10	6	15	669	<1	100	62
10/03 2.3	9900	102000	20000	800	1500	1170	700	10	6	14	660	1	100	61
10/03 2.4	10000	107500	20500	800	1500	1160	800	10	6	14	665	1	100	62
10/03 2.5	9900	121000	18800	800	1600	1170	700	10	7	14	661	<1	100	58
10/03 2.6	9600	121500	17800	800	1500	1120	700	10	6	13	644	<1	100	57
01/04 1.1	9300	103000	18400	1100	1500	1250	800	10	6	15	642	<1	100	60
01/04 1.2	9600	99700	20000	900	1500	1180	800	10	7	15	659	1	100	60
01/04 1.3	10000	110500	18800	900	1500	1140	700	10	6	15	667	<1	100	59
01/04 1.4	10300	115000	19200	900	1600	1160	700	10	6	15	682	<1	100	60
01/04 1.5	9900	116000	18900	800	1500	1140	700	10	6	15	658	1	100	58
01/04 1.6	10000	110500	19700	800	1500	1130	700	10	6	18	668	<1	100	59
01/04 2.1	9900	111500	18800	1000	1600	1260	800	10	6	14	663	1	100	61
01/04 2.2	9100	120000	17500	900	1500	1160	600	10	7	16	611	1	200	56
01/04 2.3	9900	112500	18900	900	1600	1210	600	10	6	17	640	1	200	59
01/04 2.4	10100	107000	18700	900	1600	1170	600	10	7	16	651	1	200	58
01/04 2.5	9100	105000	17600	800	1400	1030	500	10	5	15	599	1	200	53

01/04 2.6	7800	180000	13800	600	1400	890	<100	10	5	16	540	1	200	43
04/04 1.1	8600	110000	16800	1000	1500	1170	600	<10	6	17	582	1	200	54
04/04 1.2	9200	91300	17400	1000	1400	1230	700	10	6	17	597	<1	200	57
04/04 1.3	8600	122500	17400	800	1500	1090	600	10	6	17	591	1	200	53
04/04 1.4	9400	113000	18100	900	1500	1090	600	10	6	18	616	<1	200	55
04/04 1.5	9200	122500	17400	800	1500	1070	500	10	6	16	608	<1	200	53
04/04 1.6	9600	113500	17900	800	1500	1100	600	10	6	16	625	1	200	54
04/04 2.1	8900	112000	17000	1000	1500	1160	600	10	6	16	589	1	200	54
04/04 2.2	9100	102500	17100	900	1500	1180	600	10	5	16	595	1	200	57
04/04 2.3	9700	105500	18100	1000	1500	1150	600	10	6	16	619	1	200	56
04/04 2.4	9900	114500	18900	900	1600	1120	600	10	6	16	635	1	200	55
04/04 2.5	9800	120500	17400	900	1500	1120	600	10	5	16	624	1	200	55
04/04 2.6	8300	158000	14800	800	1400	970	500	<10	5	16	554	1	200	46
07/04 1.1	9400	111500	17100	1000	1500	1310	700	10	6	19	628	1	200	58
07/04 1.2	9800	112000	18300	900	1500	1200	700	10	6	18	629	<1	200	57
07/04 1.3	9800	105000	18500	900	1500	1150	600	10	6	17	623	1	200	56
07/04 1.4	9600	108500	17600	900	1500	1110	600	10	5	17	608	<1	200	56
07/04 1.5	10200	116000	18400	900	1600	1140	600	10	6	17	641	1	200	56
07/04 1.6	7100	219000	13000	700	1700	770	<100	10	4	11	490	<1	100	37
07/04 2.1	8800	97400	17700	1000	1400	1240	700	10	5	16	598	1	200	56
07/04 2.2	9600	110500	17600	900	1500	1240	700	10	7	17	642	1	200	57
07/04 2.3	9200	119000	17000	800	1500	1160	600	10	6	16	615	1	200	53
07/04 2.4	9600	110500	17800	800	1500	1160	600	10	6	16	635	1	200	58
07/04 2.5	9100	116000	16700	800	1500	1080	600	10	7	16	616	1	200	52
07/04 2.6	5500	229000	9600	500	1400	690	<100	<10	4	14	402	<1	300	30

* Where 10/03 = month/year of collection; 1.1 = oven dried 0-5cm, 1.2 = oven dried 5-10cm etc; 2.1 = air dried 0-5cm, 2.2 = air dried 5-10cm etc

Table G-3. The ICP-AES results for the plant nutrients from the samples collected from the Savernake CDB Site.

Savernake CDB Site	Plant Macro-Nutrients							Plant Micro-Nutrients						
Sample Name*	Al (ppm)	Ca (ppm)	Fe (ppm)	K (ppm)	Mg (ppm)	P (ppm)	S (ppm)	B (ppm)	Co (ppm)	Cu (ppm)	Mn (ppm)	Mo (ppm)	Na (ppm)	Zn (ppm)
10/03 1.1	9100	500	30100	1000	700	380	500	10	10	8	433	1	<100	40
10/03 1.2	10800	200	33500	1000	900	280	300	10	10	6	280	1	<100	37
10/03 1.3	11000	100	30700	1100	900	200	200	<10	10	5	284	<1	<100	36
10/03 1.4	11800	100	32200	1100	900	210	200	<10	13	5	331	1	<100	37
10/03 1.5	12900	100	33400	1200	1000	180	200	<10	13	5	260	1	<100	40
10/03 1.6	20300	100	57200	2100	1700	170	200	10	13	8	309	1	<100	60
10/03 2.1	9600	400	28400	1000	800	350	500	10	9	7	286	<1	<100	38
10/03 2.2	11300	100	31700	1100	900	240	200	<10	12	5	408	1	<100	36
10/03 2.3	11400	100	27400	1100	900	190	200	<10	8	5	151	<1	<100	36
10/03 2.4	11900	100	28000	1100	1000	180	200	<10	9	4	136	1	<100	37
10/03 2.5	14000	100	46700	1300	1100	190	300	<10	22	6	654	<1	<100	46
10/03 2.6	18300	100	57300	1900	1600	150	200	10	13	8	320	1	<100	57
01/04 1.1	7900	700	32200	900	700	400	600	10	14	10	641	1	<100	43
01/04 1.2	9900	300	32700	1000	800	260	300	10	13	8	443	1	<100	38
01/04 1.3	11000	200	31900	1100	900	190	200	<10	8	8	186	1	<100	37
01/04 1.4	11700	100	38900	1000	900	220	200	<10	13	8	356	1	<100	40
01/04 1.5	12000	100	37300	1100	900	160	200	<10	19	7	665	<1	<100	41
01/04 1.6	14000	100	35100	1300	1100	130	200	<10	9	7	216	<1	<100	46
01/04 2.1	8400	500	28600	900	700	370	500	10	8	13	280	1	<100	48
01/04 2.2	9900	200	30900	1000	800	280	400	10	9	7	279	1	<100	38
01/04 2.3	10900	200	34500	1000	900	200	300	<10	14	5	444	<1	<100	39
01/04 2.4	11800	100	33300	1100	900	180	200	<10	15	5	378	1	<100	39

01/04 2.5	12800	100	39600	1200	1000	180	200	<10	15	5	450	1	<100	41
01/04 2.6	13300	100	34400	1200	1100	130	200	<10	10	5	241	1	<100	44
04/04 1.1	9600	600	36000	1100	800	370	500	10	9	9	359	1	<100	46
04/04 1.2	11800	300	40500	1200	1000	260	300	10	10	8	326	1	<100	47
04/04 1.3	11800	100	33200	1100	1000	180	200	<10	12	8	256	<1	<100	40
04/04 1.4	11700	100	36000	1000	900	170	200	10	21	7	611	1	<100	40
04/04 1.5	11600	100	39900	1000	900	200	200	<10	16	7	437	1	<100	41
04/04 1.6	13600	100	48000	1200	1200	150	200	<10	13	10	302	1	<100	50
04/04 2.1	7500	1200	24800	900	700	480	800	10	7	12	407	1	<100	58
04/04 2.2	11900	200	40100	1200	1000	250	300	<10	11	7	329	1	<100	42
04/04 2.3	12600	100	41600	1200	1000	210	200	<10	12	6	358	1	<100	43
04/04 2.4	11500	100	32900	1000	900	150	200	<10	11	5	221	<1	<100	39
04/04 2.5	12100	100	39300	1100	900	190	300	<10	19	5	507	<1	<100	40
04/04 2.6	12300	100	43600	1100	1000	180	200	<10	15	5	434	1	<100	44
07/04 1.1	7800	1300	27700	900	700	470	700	10	7	11	355	1	<100	108
07/04 1.2	10900	400	38700	1200	900	320	400	10	8	9	242	1	<100	59
07/04 1.3	13800	200	50500	1400	1200	210	300	10	18	8	582	1	<100	54
07/04 1.4	13500	100	42900	1300	1100	210	300	<10	10	7	235	1	<100	48
07/04 1.5	14500	100	46100	1400	1200	190	200	<10	11	8	268	1	<100	49
07/04 1.6	20400	100	60300	1900	1700	190	200	10	10	10	180	1	<100	66
07/04 2.1	7400	1600	27300	900	700	500	800	10	7	10	417	1	<100	104
07/04 2.2	11800	300	43700	1200	1000	290	400	<10	10	7	307	1	<100	57
07/04 2.3	13000	200	48000	1200	1100	230	300	<10	14	6	353	1	<100	51
07/04 2.4	13300	100	43600	1300	1100	160	200	<10	14	6	349	1	<100	47
07/04 2.5	13300	100	42400	1300	1100	210	200	<10	11	6	260	1	<100	47
07/04 2.6	20000	100	65300	1900	1700	180	200	10	9	10	158	<1	<100	65

* Where 10/03 = month/year of collection; 1.1 = oven dried 0-5cm, 1.2 = oven dried 5-10cm etc; 2.1 = air dried 0-5cm, 2.2 = air dried 5-10cm etc

Table G-4. The ICP-AES results for the plant nutrients from the samples collected from the Sherwood CDB Site.

Sherwood CDB Site	Plant Macro-Nutrients							Plant Micro-Nutrients						
Sample Name*	Al (ppm)	Ca (ppm)	Fe (ppm)	K (ppm)	Mg (ppm)	P (ppm)	S (ppm)	B (ppm)	Co (ppm)	Cu (ppm)	Mn (ppm)	Mo (ppm)	Na (ppm)	Zn (ppm)
10/03 1.1	8400	300	22900	600	600	450	600	<10	1	18	118	2	100	28
10/03 1.2	9700	900	26800	600	700	360	400	<10	2	23	136	1	100	34
10/03 1.3	10600	100	27800	600	800	340	300	<10	3	13	196	<1	100	27
10/03 1.4	13400	200	29200	700	1100	340	300	<10	4	11	243	<1	100	34
10/03 1.5	17200	100	33500	1000	2000	390	400	<10	6	14	226	<1	100	55
10/03 1.6	19100	100	32000	1300	3100	340	300	<10	12	20	266	<1	100	94
10/03 2.1	8200	300	22200	600	600	590	900	<10	3	22	112	3	100	31
10/03 2.2	9900	100	26500	600	700	350	400	<10	2	14	121	<1	100	24
10/03 2.3	11700	100	29200	700	900	330	400	<10	3	13	196	<1	100	29
10/03 2.4	14100	100	29600	800	1300	340	400	<10	5	11	235	<1	100	37
10/03 2.5	17100	<100	33500	900	1800	380	400	<10	7	13	264	<1	100	51
10/03 2.6	19000	100	31700	1400	3100	330	300	<10	13	20	277	<1	100	104
01/04 1.1	9300	100	26200	600	700	390	500	<10	2	19	158	1	100	27
01/04 1.2	11200	100	28300	700	800	330	300	<10	3	16	241	1	100	32
01/04 1.3	12800	100	28800	700	900	340	400	<10	4	14	280	<1	100	37
01/04 1.4	16100	100	32000	800	1500	370	400	<10	6	16	238	<1	100	52
01/04 1.5	18700	<100	34100	1100	2500	380	400	<10	8	19	210	<1	100	79
01/04 1.6	19500	<100	32700	1300	3100	350	300	<10	12	22	240	<1	100	91
01/04 2.1	8800	200	23200	600	600	540	900	10	3	22	120	3	100	32
01/04 2.2	11400	100	28600	700	900	340	300	<10	4	13	192	<1	100	30
01/04 2.3	14800	1000	29300	1000	1100	330	400	<10	4	11	265	<1	100	35
01/04 2.4	17800	800	32400	1200	1700	370	400	<10	5	13	272	<1	100	48
01/04 2.5	21600	100	34200	1700	3100	370	300	<10	12	21	228	<1	100	99

01/04 2.6	22400	200	34800	1700	3200	400	400	<10	12	19	215	<1	200	111
04/04 1.1	10300	200	25500	800	700	400	500	<10	2	19	138	2	100	27
04/04 1.2	12000	100	27000	900	800	330	400	<10	4	36	215	<1	100	30
04/04 1.3	14100	100	28200	900	1000	320	400	<10	5	18	273	1	100	37
04/04 1.4	17600	100	31400	1100	1700	350	400	<10	6	19	238	<1	100	49
04/04 1.5	21600	100	34200	1600	3000	380	400	<10	11	21	204	<1	100	90
04/04 1.6	22200	100	34700	2000	3500	360	300	<10	13	21	254	<1	100	96
04/04 2.1	10900	200	26100	900	700	430	600	<10	3	18	155	2	100	28
04/04 2.2	12700	100	29100	1000	900	330	400	<10	3	18	220	<1	100	28
04/04 2.3	13900	100	29100	1000	900	340	300	<10	4	15	266	1	<100	37
04/04 2.4	17800	100	33600	1200	1700	350	400	<10	6	16	264	<1	<100	54
04/04 2.5	21300	100	36100	1500	2900	390	300	<10	9	21	198	<1	<100	91
04/04 2.6	21600	100	35200	1900	3300	340	300	<10	14	21	255	<1	<100	104
07/04 1.1	8400	300	22600	700	500	550	900	10	3	28	122	4	<100	39
07/04 1.2	10200	100	24800	800	700	410	500	<10	3	25	138	1	<100	31
07/04 1.3	11800	100	28600	800	800	340	300	<10	3	18	212	<1	<100	31
07/04 1.4	15100	100	30000	1000	1100	320	300	<10	4	16	258	1	<100	43
07/04 1.5	20400	<100	36000	1400	2700	400	400	<10	8	22	182	<1	<100	86
07/04 1.6	23700	100	38100	1900	3400	420	300	<10	14	26	253	<1	<100	104
07/04 2.1	9300	200	24500	800	600	480	700	10	3	21	143	2	<100	31
07/04 2.2	11300	100	27200	900	800	370	400	<10	3	16	153	1	<100	27
07/04 2.3	12300	100	29100	900	900	330	300	<10	3	16	197	1	<100	31
07/04 2.4	14100	100	29500	1000	1000	310	300	<10	4	12	290	<1	<100	36
07/04 2.5	20900	100	37000	1500	2600	380	400	<10	9	18	205	1	<100	78
07/04 2.6	22300	100	36800	1800	3300	390	300	<10	11	21	256	<1	<100	103

* Where 10/03 = month/year of collection; 1.1 = oven dried 0-5cm, 1.2 = oven dried 5-10cm etc; 2.1 = air dried 0-5cm, 2.2 = air dried 5-10cm etc

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