Valuing the Vernacular:

Scotland's earth-built heritage

and the impacts of climate change

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Statement of originality

I hereby confirm that this is an original study conducted independently by the undersigned and that the work contained herein has not been submitted for any other degree. All reference material has been duly acknowledged and cited.

Signature of candidate:

Date:

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Abstract

Scotland's vernacular earth-built heritage has received inadequate recognition over a number of decades, being the reserve of a small group of academic, architectural and conservation practitioners, with negative perceptions of the structures and their inhabitants having been developed over the long-term. This has ultimately contributed to the loss of a wide number of earth building traditions previously widespread across Scotland. Heritage custodians have invested in the restoration and maintenance of a select few sites, but wider recognition of the significance of extant structures, including the intangible aspects of inherited traditions, remains limited. This thesis therefore seeks in the first instance to promote improved understandings of Scotland's earth-built heritage through historical appraisals that underline its wider heritage value within global, regional and local contexts, whilst demonstrating the limitations of survey evidence hitherto relied upon.

Heritage policies and management procedures are increasingly driven in response to the climate changes projected for the remainder of the twenty-first century, partly informed by the impacts of changes that have already been observed. As a result of this, new fields of research such as heritage climatology have developed with a view to offering bases from which to develop longer term mitigation and management strategies that recognise potential changes to the causes and processes of deterioration in the historic environment. Alongside the development of academic interest in climate and heritage has been an ever-increasing accessibility to advanced analysis methods through technical apparatus (often portable) that can be used to create improved evidence repositories based on processes-led approaches to investigation.

Scotland's earth-built heritage is susceptible to a range of climate-related phenomena that are likely to manifest in different ways over coming decades. Conservation strategies have continued to rely, however, upon the empirical observations and the experience of very few individuals since the latter-twentieth century. Consequently, the *ad hoc* approaches to the management of Scotland's earth-built heritage and lack of strategic planning that have been typical to this point require amendment. This interdisciplinary thesis therefore seeks to contribute to addressing the issues outlined above through the exploration and application of portable scientific sampling apparatus that allow for *in situ*, rapid and non-intrusive insights to be gained at various scales of interest. These, together with other minimally intrusive approaches to assessing performance in earth building materials, allow for the development of processes-led strategies to extending the evidence base beyond that presently relied upon.

Amongst the key outcomes of this are the generation of a locally-focused dataset of climate projections that are used to develop understandings of future climate conditions in the Carse of Gowrie, Perthshire, and in turn garner insights as to how these will impact in relation to the earth-built heritage for which this region is noted. Temperature and humidity monitoring evidence gathered from within the walls of extant structures over the course of fourteen months from March 2012 to April 2013 are set against contemporary external weather conditions and alongside measurements of moisture ingress. These serve to highlight both aspects of inherent resilience and points of particular risk to the future integrity of earth-built structures. An extended benefit of this work is the demonstration that the novel procedures used are easily replicated and could be employed in a variety of local contexts to develop suites of intra-site data across Scotland, with the potential for offering evidence-based inferences relevant to management procedures and policy discussion. The utility of the understandings and methods of investigation long established in the field of soil science but conspicuously overlooked in earth buildings research is also addressed, with insights into micro-scale processes offered using micromorphological and micromorphometric methods and the results being directly related to macro-scale observations.

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List of thin section abbreviations

Thin sections subjected to micromorphological and micromorphometric analyses were produced from samples gained in the field and from subsamples removed from materials following treatments in two different experiments. These thin sections are referred to using codes in Chapter 10, which relate to their original field site context or experimental provenance (the latter of which is explained in Chapter 6), and the following guide should be referred to for clarification.

Field sample thin sections

CoLo	Cottown Lower
CoUp	Cottown Upper
Flex	Flatfield External
Flin	Flatfield Internal
FG5NR	Fort George Wall 5 Non-rendered
FG5R	Fort George Wall 5 Rendered
Lee	Leetown

Winter-spring experiment thin sections

WS100DBS	Winter-Spring 100 Dry Baseline
WS25DBS	Winter-Spring 25 Dry Baseline
WS20DBS	Winter-Spring 20 Dry Baseline
WS15DBS	Winter-Spring 15 Dry Baseline
WS100WBS	Winter-Spring 100 Wet Baseline
WS25WBS	Winter-Spring 25 Wet Baseline
WS20WBS	Winter-Spring 20 Wet Baseline
WS15WBS	Winter-Spring 15 Wet Baseline
WS100D2080	Winter-Spring 100 Dry 2080s
WS25D2080	Winter-Spring 25 Dry 2080s
WS20D2080	Winter-Spring 20 Dry 2080s

WS15D2080	Winter-Spring 15 Dry 2080s
WS100W2080	Winter-Spring 100 Wet 2080s
WS25W2080	Winter-Spring 25 Wet 2080s
WS20W2080	Winter-Spring 20 Wet 2080s
WS15W2080	Winter-Spring 15 Wet 2080s

Freeze-thaw experiment thin sections

FT100BS	Freeze-Thaw 100 Baseline
FT25BS	Freeze-Thaw 25 Baseline
FT20BS	Freeze-Thaw 20 Baseline
FT15BS	Freeze-Thaw 15 Baseline
FT1002080	Freeze-Thaw 100 2080s
FT252080	Freeze-Thaw 100 2080s
FT202080	Freeze-Thaw 20 2080s
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Thesis structure

The introduction provides an outline of the framework within which the research conducted for the project sits, with the resultant thesis spanning disciplinary boundaries across documentary history, environmental history, climate science, heritage climatology, conservation science and geoarchaeology. The thesis is therefore thematically delineated after the introduction according to these divergent but complementary parts. Some essential background information is provided in the introduction, including explanation of a range of terminologies relevant to studies of the earth-built heritage, notes on the nature and properties of typical soil materials used in construction and the growth in interest in earth building traditions and conservation over the last half century or so.

The opening part is comprised of three complementary and progressively focused chapters. The first, building on the introductory notes, elucidates on the international context in which studies of earth building must be grounded through reference to the continuities and divergences found in traditions globally. From this starting point the historical considerations are scaled down to a gradually more localised perspective, with insights sought from noteworthy studies of vernacular and earth building across England, Wales and Ireland as a means of augmenting the evidence gained in relation to Scotland. Explanations of the history of Scottish earth building are then provided, with a particular focus on mudwall techniques, based on the synthesis of novel evidence and the consideration of prior studies. This ultimately serves to stress the heritage value of Scotland's earth-building traditions and provides justification for the need to improve the evidence base used in the conservation and management of extant structures.

Having established the heritage value of Scotland's vernacular earth-built heritage through a consideration of its historical significance, the second part, on projected climate change and heritage climatology, provides a fulcrum upon which the historical, heritage and technical aspects of the interdisciplinary research are balanced. The research context of climate science and projected climate change is provided as the starting point for this section, emphasising the integrated and holistic approaches to mitigation that have been necessarily developed in reaction to the series of International Panel on Climate Change (IPCC) reports up to 2007. This provides the rationale for incorporating considerations of climate change impacts into heritage policy and, therefore, emphasises the importance of research undertaken within the emergent sub-discipline of heritage climatology. Discussion is afforded to the under-appreciation of climate change impacts upon the earth-built heritage of Scotland and how pre-existing understandings of weather-related deterioration may be used to inform further research into the potential for future patterns of deterioration. This ultimately leads to the examination, through utilisation of the UKCP09 Weather Generator, of climate scenarios based on baseline and projected climate data for the Carse of Gowrie, in Perthshire, which provides the main case study area to where the majority of sampling and analysis relates. These downscaled climate projections are then used to inform the development of climate cabinet experiments using earth blocks designed to be analogous with mudwall building materials found in Scotland. These blocks are subjected to treatments based on data generated for a baseline climate period (the late-twentieth century) and a projected future climate period (the late-twenty-first century) in order to comparatively assess the deterioration of the materials in relation to each other and those collected from the field. These assessments are explained primarily at the end of the final main section, after discussion of field sampling and the analysis of materials extracted from historic structures in the Carse of Gowrie, although observations of the blocks following treatment are provided following explanations of the experimental methodology.

The third part of the thesis builds upon the context of heritage climatology and threats to earth buildings discussed in the previous chapter to explain the strategy, methods and results of fieldwork conducted within the Carse of Gowrie, Perthshire, with a particular focus on the case study of the Old Schoolhouse, Cottown. This is then followed by the results of the micromorphological and micromorphometric analyses of thin sections derived from field samples, as well as those derived from the post-treatment experimental earth blocks. An integral aspect of the process of sampling and analysis has been exploring the application, through experimentation, fieldwork and case study, of techniques previously unemployed in the assessment of Scotland's earth-built heritage. To this end, a hierarchical model of non- and minimally-destructive monitoring and sampling activities is outlined, including the use of temperature and humidity monitoring probes, microwave moisture sensor survey, X-ray diffraction, portable X-ray fluorescence, near infrared spectroscopy, X-ray computed tomography and micromorphological and image analysis techniques. The use of these latter two methods of analyses allows for direct comparisons between field samples and experimental materials.

The thesis conclusions then follow, with the intention of emphasising the importance of integrating divergent approaches to researching the built heritage. Recommendations of how to extend and improve the methods utilised over the course of the research period are also provided, together with suggestions of the principal outcomes of the study.

Glossary of earth building terminologies

At this point, it is essential to clarify a range of terminologies germane to some of the descriptive and technical aspects of the thesis before delving into the main body of text.

Adobe: unfired earth bricks or blocks found across vast swathes of the arid parts of the globe in a great array of architectures. Traditionally, these could be shaped by hand or pressed into wooden moulds before being allowed to air dry. The term is also used in reference to entire structures, typically in the south-west of the United States of America.

Cob (also see **mudwall**): the most universally-recognised term for the wet method process of earth building technique prevalent in south-west England whereby well-graded clay-rich subsoil is mixed with organic fibrous matter such as straw and, if necessary, coarser mineral material, together with enough water to reach a malleable consistency. Traditionally mixed on the ground by the trampling of the builders or their animals, the earthen material would be lifted using an agricultural fork onto a low stone plinth wall in successive layers, or lifts, before being trodden and beaten into shape and then pared to shape the external surface. The height of each lift would be determined by the characteristics of the raw materials used and skill and requirements of the builders. Walls would typically be raised over a number of weeks throughout the summer period, although some records suggest that in places such as around the Solway Firth walls could be raised in a single day as part of a communal effort. Cob walls generally bulge towards the bottom due to the weight carried above, with the slow process of solidification occurring as the material dries *in situ*.

Dry method: refers to processes by which walls are raised without having recourse to the addition of water to build a mass earth wall. This means that dry method building refers to the *pisé de terre* or rammed earth technique (see below).

Earth; **earthen**: used here in the generic sense to denote soil (see below) material used in the erection of walls, thus encompassing the vast array of materials from clays to turf or peat.

Earth building; **earth-built**; **earthen architecture** etc.: used as general terms to encapsulate the full spectrum of structures erected using unfired soils as an integral walling constituent. It should be noted that references to 'architecture' usually infer a distinction from vernacular structures, such as in the case of contemporary adobe structures in the south-west USA, although this delineation is somewhat blurred by the inherently vernacular nature of local unfired earth as a building material, even when employed in monumental and ornate buildings.

Liquid limit: the point at which soil loses coherence as a malleable material due to excess water content leading to the mineral matter being held in suspension. This, together with the plastic (see below), shrinkage, adsorption and adhesion limits were defined by Atterberg as a means of expressing the strength characteristics of soils, with the tests of these states known as the Atterberg Limits.

Mass earth: an umbrella term referring to monolithic walls built with a solid mass of earth, without recourse for structural support. As such, this includes rammed earth, adobe and cob/mudwall walls, all of which can be loadbearing and continuous from ground-level to eaves.

Mudwall: the most widely-used term across much of the United Kingdom and Ireland to describe the cob building technique, recorded as a place-name in 1395 in London and in 1497 in Essex (McCann, 2004). A great deal of alternative regional terms are also known, however, including *clom* or *mwd* in Wales; wychert in a small enclave of Buckinghamshire where lime and pebbles are used together with the clay subsoil; and, the clay dabbins of the Solway Plain.

Pisé de terre (hereafter ***pisé***) or **rammed earth**: a method of earth building whereby the raw material is used without additional water and the walls are raised in layers between removable formwork, with ramming equipment used to compact each layer of added soil. This process produces a wall that is perpendicular to the ground from base to top.

Phase change: a change to the state of a physical substance, for example the freezing of water (liquid to solid) or crystallisation of salts (liquid to solid). Such changes may have deteriorative implications where they have occurred within building materials and can be subject to variation in frequency, duration or extent as a consequence of external weather conditions. Therefore, changes to climate will impact on the annual mean occurrence of certain phase changes, for example the crystallisation of Na_2SO_4, and as a result exhibit different patterns of manifestation.

Plastic limit: the point at which a malleable mass of soil dries and shrinks to the point of breaking into 10-20 mm sections when rolled into a thread of about 3 mm diameter. Higher plasticity in a soil is associated with greater susceptibility to swelling and shrinkage. It should be noted the definition of plastic limit generally used in the earth building community differs from the technical definition employed more formally in soil science.

Soil: highly heterogeneous and dynamic porous media found at the terrestrial surface of the earth and originally formed through the weathering of surface rock or geological sediment (the parent material) as a result of geological, topographical, climatic, physical, chemical and biological factors. Together with weathered inorganic and mineral material, the action of living and decaying organic matter is also integral to the definition and characteristics of soils. Soils are comprised *in situ* of one to several distinct layers of varying possible thickness, referred to as horizons, which reflect different physical properties and stages of weathering. The mineral material components of soil in descending order of size are boulders, stones, gravel, sand, silt and clay. Together with mineral material and organic matter, gases and liquids are intrinsic to soils, being free to move through them as a result of their inherent porosity.

Vernacular: refers to materials, methods and traditions that are locally distinct and used in response to their own local context without recourse to formalised practices. Scotland's earth building traditions are therefore considered vernacular through the employment of local soils and craft traditions throughout the construction processes by which they came into being.

Wattle and daub: a method of building used in many parts of the globe over millennia that involves the application of mud (daub) to woven branches or slats fixed in place by stakes.

Wet method: refers to earth building techniques that require water to be added to soil material during the mixing process in order to achieve a workable consistency. This allows for the building of cob walls; the manufacture of mud bricks and blocks, which are dried prior to building in the same manner as a masonry wall; or, the daubing of wattle-work and application of earthen material between timber stakes.

Introduction

1. Introduction

This thesis is structured using hierarchies of scale, with increasingly localised foci applied to the historical and climatological aspects of research and the integrated use of macro-scale to micro-scale sampling and analysis techniques reflecting the universal immediacy of the relationship between earth buildings and their landscapes (Fig. 1.1). The local landscape contexts within which earth-built structures are found are highly diverse, but the majority of studies of earth building techniques, traditions, deterioration and conservation relate to the arid parts of the globe in which unfired earth remains a primary construction material after centuries or millennia of continued use.

Fig. 1.1. The two-tone town of Ighir-n-Tissent, in the Bon Ouli valley, Morocco, encapsulates the extent to which earth building traditions reflect local soil resources. (Photo credit: Pablo Muñoz Carballeda).

1.1 Earth building research in Scotland

Scotland also has a long tradition of earth building, however, with clay-rich subsoils, loose soil, turf and peat known to have been employed from the Neolithic in the walls, floors and roofs of structures across the architectural spectrum. There is an intrinsic irony that the prevalent clay-rich landscapes that facilitated the development of local earth building traditions in Scotland also have the potential to act as a contributory cause of building failure due to their propensity for retaining water and encouraging its uptake into the walls of buildings, a point acknowledged in guidance on historic buildings' conservation produced by Historic Scotland (Urquhart, 2007).

The accumulated knowledge of earth building materials and methods that had been acquired and maintained in Scotland over millennia was completely lost by the time that the heritage value of extant structures received recognition in the later-twentieth century. To date, the study of Scotland's earth-built heritage has been the reserve of a limited body of scholars since the second half of the twentieth century and scientific considerations relating to processes of deterioration have received far less attention than the surveying and recording of surviving examples (Walker, 1977; Fenton and Walker, 1981). The inexperience of heritage custodians in Scotland when dealing with vulnerable earth-built structures was noted in the mid-1990s (McGregor and Walker, 1995) and Historic Scotland has since committed resources to vernacular buildings' research that has produced Technical Advice Notes on earth (Walker *et al*., 1996; McLaughlin, forthcoming), turf (Walker *et al.*, 2006), and the Hebridean blackhouses (Walker and McGregor, 1996). Their provision of a brief technical guide on earthen building materials, as part of the *Inform* series, also offers practical guidance to custodians and owners of historic structures with earth components (Historic Scotland, 2011). Historic Scotland also supported a programme of field experiments on earth building materials and techniques that took place between 1996 and 2004, although the results of this were never published and are only publicly available in summary form from the website of a commercial architectural practice (Morton, 2004).

Within the last twenty years the National Trust for Scotland (NTS) has utilised resources, in collaboration with partner stakeholders, to conserve and renovate two mudwall structures at risk of being lost. Great success in this endeavour was achieved under the NTS Little Houses Improvement Scheme at the Logie Schoolhouse, in Angus (Chapter 4, fig. 4.3). This early- to mid-nineteenth century single-storeyed mudwall structure (Romankiewicz, 2005; AOC Archaeology Group, 2008) was taken from a point of dereliction to complete restoration as a one-bedroom dwelling (Copp, 2009), leading to a prestigious Europa Nostra Award for cultural heritage conservation. Assessments of U-values, which refer to the thermal performance of building elements such as walls, floors or roofs in terms of their rate of heat transfer, have since been conducted at Logie Schoolhouse and indicate the excellent insulating properties of mass earth buildings in comparison with other traditional dwelling-types found across Scotland (Historic Scotland, 2011). Unfortunately, the success of the restoration works at Logie Schoolhouse has not been replicated at the Old Schoolhouse in Cottown, Perthshire (Chapter 7), despite the initial investments made in its conservation and restoration and attempts to develop the site through the same channels as at Logie. The Cottown Schoolhouse provides the thesis with its central case study and exhibits myriad management issues that have prevented full redevelopment and the long-term security for the structure that this would bring.

Previous research commissioned by the Scottish Executive resulted in the publication of a report that highlighted the contemporary appropriateness and future viability of earth building in Scotland, as a response to the development of sustainability agenda at the turn of the new millennium (Little and Morton, 2001). Despite this, interest in earth building in a commercial capacity has remained relatively limited, with the unfortunate closure of the historic Errol Brickworks in 2008 meaning the loss of Scotland's only manufacturer of unfired earth bricks. Spanning commercial and conservation interests in earth building traditions and techniques, Morton (2008) has played an important role in highlighting the heritage value and future potential of earth building and reported on the use of turf capping as a means of conserving the heads of masonry walls (Historic Scotland, 2011, vols. 1 and 2). Nevertheless, a general over-reliance on anecdotal evidence and a small body of academic studies has hitherto resulted in a rather *ad hoc* approach to the management of Scotland's remaining earth buildings, reflecting a wider situation across the United Kingdom.

1.2 Approaches to the thesis

Building upon the situation outlined above, whilst accounting for the increasing emphasis placed on climate change in heritage research and policy development, this thesis seeks to marry historical appraisals of Scotland's lost and hidden stock of vernacular earth buildings with novel scientific approaches to understanding climate-related processes of deterioration in extant walling materials. The intention is that this should contribute to improving the conservation and management of Scotland's earth-built heritage. The objectives of the thesis can thus be summarised as responding to the following key research questions:

- What defines the value of Scotland's earth-built heritage and how can historical research be used to explore this?
- How will projected climate change affect processes of deterioration in Scotland's earth-built heritage?
- Can novel approaches to monitoring and assessing the underlying causes and processes of deterioration in earth building materials be developed?

The focus is placed on the mass earth traditions that occur within the wider body of Scotland's earth-built heritage, with documentary evidence used to emphasise the past ubiquity of vernacular mass earth buildings and assess how perceptions of such structures developed over time. It was decided to follow this path because mudwall and claywall techniques can be found across different landscapes within Scotland and further afield, yet simultaneously are locally few in number and require closer consideration in the short term to ensure their recognition and preservation. Furthermore, in order to generate useful results from studies utilising a wide range of sampling equipment and analysis techniques, it was deemed important to consider a more discrete set of building typologies and a set of sampling sites between which useful comparisons could be explored. Given the inherent variability of earthen building materials, it was also determined that the research should focus on walls erected entirely with admixtures based on clay-rich soil. This necessarily removes considerations of turf and earth-bonded stone walls from the technical considerations encountered from Chapter 5 onwards.

Heritage is wide-ranging in its scope, comprising things such as buildings, monuments, sites, landscapes, objects, traditions and collective experiences inherited from the past that are deemed as carrying intrinsic value to society in the present and will continue to enrich society in the future. Heritage can therefore be both tangible and intangible. The earth-built heritage of Scotland falls into both of these categories, constituting upstanding structures that serve as examples of vernacular building practices, local connections with landscape and the understanding and application of accumulated craft knowledge. Global and regional contextualisation is an important starting point in exploring these universal themes, whilst historical perspectives provide explanation of the significance of Scotland's earth building traditions in terms of cultural heritage value.

The terms "value" and "significance" are familiar to those who work in the heritage sector. Nonetheless, these remain loosely defined and subject to variable interpretations between individuals. The notion of value is fundamental to heritage policy, management and promotion. This is reflected in the UNESCO stipulation that a heritage site must be proven to meet the criteria of 'outstanding universal value', or OUV, in order to become enshrined on the World Heritage List (http://whc.unesco.org/en/criteria/). Although assessments of heritage value and significance are clearly vital to explaining why certain inheritances from the past are worth preserving, this framework also leads to the conceptual stratification of historic sites, environments, traditions and artefacts, perhaps at the cost of those that represent the foundational rhythms of everyday life in the past. In simple market terms, heritage value can also be qualified through rarity: the fewer the number of examples of a historically significant building, object or tradition there are, the greater the value they possess.

Attempts to quantify the significance of specific heritage assets are often made for the purposes of developing planning proposals, compiling heritage components of environmental impact assessments or designating a building with listed status. The formal categorisation of heritage significance within an economic framework helps to keep conservation within the interest spheres of developers and politicians, but often misses the underlying social value of traditions inherited from the past. Scotland's earth-built heritage is partly an expression of social history that also carries evidence of traditional understandings of construction in response to environment. The elucidation its historical significance can therefore follow a similar trajectory to the principles set out in the International Councils on Monuments and Sites' (ICOMOS) *Charter on the Vernacular Built Heritage* (ICOMOS, 1999). This specifically refers to cultural expression at the community scale, particularly in relation to landscape, within a global framework of diversity. Interestingly, this ICOMOS charter identifies 'the forces of economic, cultural and architectural homogenisation' as principal threats to the vernacular built heritage worldwide. This is undoubtedly of great concern but it should be remembered that such forces have had growing influence in Scotland over the long-term and took particular hold in the period of Improvement. This point will be explored in further detail in Chapter 4. Scotland's earth-built heritage also carries substantial cultural value through its place amongst fundamental vernacular building practices worldwide and the relatively recent inversion of its prominence in the everyday lives of Scottish people, which can now only be expressed through analyses of historical significance and past perceptions. The appreciation of past prominence therefore helps to remind us of the significance of the upstanding vernacular buildings within contemporary society, with the loss of a once ubiquitous set of everyday traditions that are now embodied in a relatively meagre number of upstanding structures helping to further define the value of Scotland's earth-built heritage. This resonates with bottom-up perspectives that acknowledge local connections to heritage through landscape (Robertson, 2012b) and thus fit with the culture of vernacular building. The built heritage is critical to the character of places and earth-built structures perhaps offer the most direct expression, within this facet of the historic environment, of the connection between people and landscape.De Angelis D'Ossat (1972) encouraged the study of historic monuments and their deterioration within a local environmental framework, and this rings especially true in relation to earthen buildings that are such tangible products of their locale and particularly susceptible to the vagaries of climate and weather. Scientific investigations focused locally on the Carse of Gowrie, Perthshire, have aimed to complement efforts within the heritage community to mitigate for the effects of future climate on the built heritage based on the accumulated experience and empirical observations of conservators. Thus, an investigative programme utilising laboratory-based experimentation and *in situ* field sampling has been followed in accordance with this aim, using downscaled climate model data and known pathways of deterioration as a starting point from which to build a novel evidence base that can be used to inform understandings of earth buildings in Scotland and further afield.

1.3 Soils as building materials

Understandings of earth building are intrinsically linked to understandings of the soils that, together with additives such as organic fibrous matter, provide the raw materials for construction. This is recognised in Houben and Guillaud's seminal text on earth building, first published in Marseille as *Traite de construction en terre de CRAterre* (Houben and Guillaud, 1989), which provides an overview of earth building as technical subject matter, 'approached from the same high levels of technology and science, as other construction technologies' (Houben and Guillaud, 1994, xii). This sought to provide a bridge between global traditions and modern, scientifically-informed construction and serve as a manual for prospective earth-builders, although it does not engage with the approaches to sampling adopted in this thesis.

The physical, chemical and biological processes involved in the development of soils (pedogenesis) from the weathering of parent rock have been summarised by White (2009) and there exists a great field of research devoted to this subject. This thesis essentially treats the samples removed from mudwall structures as anthrosols, which are described in the *World Reference Base for Soil Resources* as 'soils that have been modified profoundly through human activities, such as addition of organic materials or household wastes, irrigation and cultivation' (IUSS Working Group WRB, 2006, 71). This definition relates primarily to soils that have been heavily amended for agricultural purposes, but it also emphasises the recognition afforded to soils as anthropogenic constructs, found in contexts specifically related to the human utilisation of these naturally-occurring materials. It is useful to remember that different specialists perceive soils variably. Of primary importance to understanding soils used in construction, however, are the various particle types from which any given soil is constituted (with clays being critical), physical characteristics such as structure and texture and interactions between soils and water. The latter of these is the most acute consideration in relation to the deterioration and conservation of the earth-built heritage in Scotland.

Soils are porous materials, composed in the simplest terms of minerals, organic matter, water and air, which exhibit varying properties through a vertical profile that relate to the extent to which various weathering processes have occurred over time (White, 2009). One specific example relevant to many earth building traditions around the world is the formation of loess soils, which are the product of post-glaciation, windblown deposits of silt and clay across large areas of China, northern Europe and North America (Velde, 2008b). The different layers found in soils are broadly classified as ‘H’ and ‘O’, organic surface horizons; ‘A’, the horizon immediately below the surface, which contains humified organic matter in conjunction with mineral material; ‘B’, the subsoil, with clays and leached minerals; ‘C’, the broken parent rock material; and, ‘R’, the indurated parent rock (Chesworth, 2008). There is no international consensus as to the delineation of particle sizes in soils, but the British Standard (2006) defines clay as the particles up to a diameter of 0.002 mm (2 μm), this can also include non-clay minerals such as quartz (Velde, 2008a); silt as between 0.002 mm and 0.06 mm; fine sand as between 0.06 mm and 0.2 mm; medium sand as between 0.2 mm and 0.6 mm; coarse sand as between 0.6 mm and 2 mm; and, stones as over 2 mm. The varying proportions of these particles within a given soil determines its textural classification, following Hodgson (1974) (Fig. 1.2), this being intrinsically related to the behaviour of soils when mixed with water. It is clay-rich subsoils that are primarily used in cob/mudwall building, these being malleable (or plastic) when mixed with water, up to the point of liquid limit, and consolidating to a hard mass upon drying.

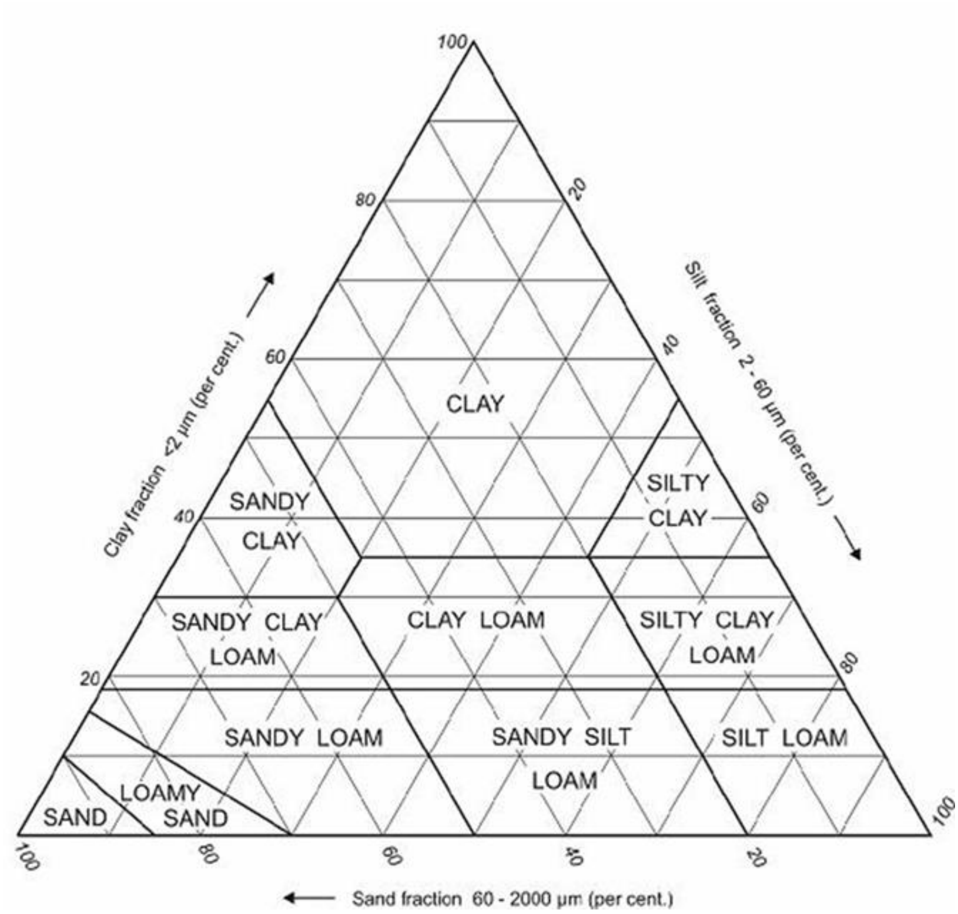


Fig. 1.2. British Standard textural classifications of soil, after Hodgson (1974).

Clay mineralogy and chemistry is an extremely complex field of research and there is a variety of clay types, all of which exhibit different properties relevant to the performance of earth building materials. The clay fraction in a soil provides a binding agent between the coarse particles, but because clay minerals have the capacity for absorbing water this also results in the susceptibility of earthen walls to failure as a consequence of shrinkage upon drying or slumping as a consequence of the liquid limit being reached following water infiltration. The coarse fraction in a soil or earth building mix works to limit the deteriorative effects of water infiltration, however, with low adsorption between particles limiting the extents of swelling and shrinkage (Houben and Guillaud, 1994). Keefe (2005) has summarised the main considerations for prospective earth-builders as being soil type, particle size distribution, percentage clay fraction, soil consistency (determined by cohesion and plasticity), soil expansiveness (determined by the type and proportion of clays), compressive strength and soil density. Well graded particle size distribution is said to be particularly crucial to the performance of cob or mudwall, with a limit of between 10 and 25% clay and relatively constant levels of the coarser fractions suggested as suitable by Keefe. It should be noted, however, that clay soils used in construction are often of a very high percentage of silt and it would seem that there is often a blurring of the boundary between the two smallest particle sizes that would not be adhered to in the strict guidelines of soil science. Watson and Harries (1995) suggested that around 35% of clay and silt combined produces an appropriate level of strength in cob walls. Analysis of clay soils used in traditional constructions from the perspective of soil science have suggested that soils with less than 20% clay, with this fraction most appropriately composed of kaolinite, are ideal (Kouoakou and Morel, 2009). The terminological disparities between soil science and much of the general literature on earth-building clays is highlighted through the fine particle size distribution assessment of bulk samples obtained from historic earth building materials from structures across Scotland, conducted as a preliminary activity in the early part of the research project (Table 1.1). Indeed, in conservation literature a typical reference to clay might explain it as ‘any fine-grained soil material which expands when wetted, becomes plastic and can be moulded when moist and shrinks and hardens on drying’ (Harrison, 1999, 13), without recourse to details of greater complexity.

Table 1.1. Particle size distributions (up to 2000 µm) for preliminary samples obtained from around Scotland.

Particle diameter (µm)	Errol brickworks clay subsoil, Perthshire, volume %	Logie Schoolhouse , Angus, volume %	Flatfield Steading, Perthshire, volume %	45 High St Brechin, Angus, mud mortar, volume %	Merchant’s House, Brechin, Angus, mud plaster, volume %	Dwelling at Fladdabister , Shetland, wall mortar, volume %
<2 (clay)	14.4	3.6	6.23	7.49	4.53	2
2-63 (silt)	85.6	23.4	67.3	47.8	50.6	30.8
63-212 (fine sand)	0	15.1	17.6	20.8	28	29.5
212-630 (med. Sand)	0	31.8	7.89	20.1	10.7	22.7
630-2000 (coarse sand)	0	26.1	0.98	3.81	6.17	15

Velde (2008a) has also provided an account of clays relevant to earth building, noting that the surface properties of sheet-shaped clay minerals, including electrical charge, is crucial to their behaviour. The attraction of water molecules to the large surface area of clay minerals, known as van der Waals bonding, provides linkages between the mineral particles and thus results in a viscous mass. Swelling clays such as smectites (montmorillonite, for example) are able to incorporate water into their structure, causing expansion of up to 75% by volume, which emphasises the importance of identifying the mineralogy of clays in historic building materials using X-ray diffraction. This technique identifies the distances between layers of clay minerals, either 7, 10 or 14 Å depending on the amount of oxygen and hydrogen present, which in turn denotes the structure as being either 1:1, 2:1 or 2:2 tetrahedral to octrahedral layers. Kaolinite, micas and illites are examples of non-swelling clay minerals, whilst mixed-layer minerals are also found with compositions of micas and smectites most abundant. It is important to note, however, that swelling as a result of the incorporation of water between particles occurs across all types of clay and can have major impacts on the structural integrity of building fabrics (Rodriguez-Navarro, 1998). The addition of fibrous material to 'wet-method' earth building mixtures used in cob or adobe construction therefore not only improves cohesiveness when in a plastic state, but also distributes shrinkage cracks so as to prevent major fractures developing in the wall and increases tensile strength (Keefe, 2005).

1.3.1 Vitruvius on earth building materials

it was the discovery of fire that originally gave rise to the coming together of men...they began in that first assembly to construct shelters...some...made places of refuge out of mud and twigs

Vitruvius' *De architectura* (commonly referred to as the *Ten Books on Architecture* [Morgan, 2005]), written in the first century BC, is the oldest surviving body of work written on the subject of architecture and building engineering and the only one known to survive from the ancient world. The treatise is mostly concerned with major construction, but it also recognised the fundamental importance of vernacular materials in forging built environments, alluding to the natural convenience to early humans of using readily available materials such as mud and twigs to mimic swallows' nests. In seeking to describe the building practices of early human societies, Vitruvius also looked contemporarily to what he deemed the more primitive dwellings of barbarians as a means of ethnographic record. Notions of earth buildings and their inhabitants as being inferior or backward are encountered through medieval and early Modern commentaries relating to Scotland (Chapter 4) and are consistently associated with the perceptions of outside agencies. It is important to note, however, that it is the identification of unfamiliar populations as different, whether socially or in terms of nationality or ethnicity, that links the recurrence of this theme, with the nature of their material surroundings being offered as proof of inferiority.

Vitruvius was aware of the relationship between environment, including natural resource provision, and methods of construction. His description of the homes of the Phrygians emphasises the adaptability of vernacular construction in light of environmental context, recognising their semi-subterranean, mounded earth homes as a response to an arid, treeless setting. This discussion gives rise to a common observation regarding the merits of earth buildings, as Vitruvius notes the warmth of the Phrygians' homes during the winter and their coolness through the summer. When discussing the material requirements of earth suitable for making unbaked bricks, Vitruvius emphasises the importance of particle size in the maintenance of cohesion. He states that excess sand, pebbles or gravel not only makes bricks too heavy but also causes them to disintegrate when exposed to rain. Vitruvius makes it clear that straw was commonly used to add strength to bricks (as is attested to through archaeological evidence at ancient sites) as he notes that such fibrous matter loses its efficacy as a binding agent when associated with overly rough particles. The quality of unfired earth bricks is also said to be related to the season of production and length of drying time, with the temperate periods of spring and autumn best to allow even drying. Vitruvius explains that the extreme heat of the Mediterranean summer causes accelerated baking of bricks without allowing proper internal drying. This non-uniform drying encourages cracks to develop at the surface as the remainder of the brick dries and shrinks, ultimately resulting in weakness. It is claimed that two years' drying time is required to make bricks most serviceable. Although Vitruvius' experience of earth building materials was inevitably based on evidence from the ancient Mediterranean world and there may be gaps and simplifications in his assertions, the principles related by him generally hold true as universal guidelines for earthen construction methods and can be identified in many of the traditions discussed in the following pages.

1.4 Background to the contemporary interest in earth buildings

The subject of earth building is frequently defined in terms of experiencing a modern renaissance, with the reappraisal of traditional materials being stimulated by an international interest in ecologically-responsible building agenda (Germen, 1979; Houben and Guillaud, 1994; Keefe, 2005; Pacheco-Torgal and Jalali, 2011), including aspects such as embodied energy, thermal performance and increased understandings of healthy internal environments (Houben and Guillaud, 1994; Minke, 2000; Keefe, 2005; Morton, 2008; Röhlen and Ziegert, 2011). Social and economic considerations have also variously stimulated interest in the merits of earth as a cheap and accessible means of building shelter at times of shortage or crisis. Clough Williams-Ellis is perhaps the most renowned advocate of earth building from twentieth century Britain, with his assertion that the materials and housing shortage that followed the Great War could be alleviated 'through the use of natural materials already existing on the site, materials that could be worked straight into the fabric of the building' (Williams-Ellis, 1920, 28). Following the Second World War there was a pronounced increase in earth construction across central Europe as devastated areas were rebuilt and, although this was soon rejected in favour of "modernisation" in much of the Communist bloc (ICOMOS France, 2011), in such places as rural Moldova around 60% of new houses were still built using earth at the end of the last century (Munteanu, 2000). In the 1980s the International Institute for Environment and Development sought to emphasise the virtues of earth building as a means of solving ‘Third World’ housing problems, with the neatly encapsulated dichotomy that ‘Mud is at once the most widely used and the most neglected building material in the world’ (Agarwal, 1981, 7). Thus, it must also be remembered that developed-world perceptions of earth as a building material worthy of reconsideration overlooks the fact that across substantial portions of the globe earth-building traditions have remained unbroken after millennia (Oliver, 1983). The commonly-quoted statistic that one-third (Houben and Guillaud, 1994; Warren, 1999), or even up to one-half (Easton, 1996; Rael, 2008), of the global population occupies earth-built structures was first calculated early in the nineteen-eighties and has been a mantra repeated in related texts, research papers and conference presentations since, augmented by the notion that around half of the world population still lived in traditional village settings (Bourgeois, 1989). Jaquin has recently questioned the contemporary validity of this calculation, however, citing increases in population and urbanisation in much of the developing world over the last three decades as reasons to consider revising the proportion of those who dwell in earth buildings to closer to one-quarter (Jaquin, 2013). Regardless, the global contemporary relevance of earth building is undeniable and founded upon a rich heritage of craft traditions, monumental architectures and environmentally-stimulated ingenuities of construction, making the global context an essential starting point from which to then consider earth building at a local scale over the first chapter.

1.4.1 Interest in the deterioration and conservation of earth-built structures

It is widely acknowledged that protection from water ingress, through appropriate roofing, use of stone plinth walls and rendering, as an inherent part of the original design of an earth building, together with regular maintenance are key to ensuring the longevity of earth-built structures. Modern studies into the underlying processes of deterioration in historic earth-built structures stem from the work of Carter and Pagliero (1966), who investigated the ingress of water and solutes into mud brick walls in relation to macro-scale deterioration such as cracking at depth, surface flaking and undercutting at the base. Carter and Pagliero also commented on the effects of weathering caused by wind, with their findings being built upon through subsequent research by the likes of Torraca *et al.* (1972), who discussed the effects of plant and animal activity in undermining earthen structures and McIntosh (1974), who further considered the processes by which soluble salts could cause damage in West African mud brick structures. A general growth in interest in the conservation of the global earthen architectural heritage can also be traced through the series of international conferences on the subject supported by the International Council on Monuments and Sites (ICOMOS), which began in Yazd, Iran, in 1972. The original focus of these meetings was on mud brick buildings, with this specification being carried in the titles of the first four events. Since the fifth meeting, held in Rome in 1987, the conference names have been amended to include the full spectrum of earth building methods. A review of the conferences up to year 2000 was provided by Matero and Cancino (2002), who identified a great increase in earth buildings' research through the 1990s. Only 1% of all articles submitted to the conferences surveyed by the authors were concerned with cob, however, thus emphasising a gap in historical and conservational understandings that remains to be filled. Conferences have since been held in Yazd in 2003, in Bamako, Mali in 2008 and most recently in Lima in 2012. This was the eleventh instalment in the series and was used as a vehicle for disseminating some of the initial outcomes of the research from which this thesis emanates to a wider international audience (Adderley *et al.*, 2012). One primary focus of global interest in the conservation of the earth-built heritage relates to the impacts of seismic activity. This was reflected in the simultaneous running of *SismoAdobe 2012* as part of the programme for *Terra 2012* and indicates the contemporary prominence of earthen buildings in many parts of the globe that are at risk from earthquake. A consequence of the gradual increase in interest in earthen architecture and its conservation has been the emergence over the past three decades of key collaborative stakeholders and research co-ordinators with remits specifically targeted to the global earth-built heritage. These include CRAterre, the Getty Conservation Institute and the ICOMOS, including its dedicated sub-group the International Scientific Committee on Earthen Architectural Heritage (ISCEAH).

The World Heritage Earthen Architecture Programme has been co-ordinated by UNESCO since its inception in 2007 as part of a ten-year project to conduct conservation, restoration and training activities across parts of the globe with prominent earth building traditions (UNESCO, 2012). This programme has been outlined and conducted with a strong emphasis on sustainable development, within a framework of seeking to improve management strategies and disseminate advice on best practice, which in turn reflects the often *ad hoc* nature of decision-making in earthen heritage conservation. This has been noted in the more general sense by ICOMOS (2009) and was previously emphasised by Houben, Balderrama and Simon (2004) in relation to studies of earth building and the comparatively recent development of interest in improving scientific understandings of earthen materials and the forces of cohesion by which they operate. Typical approaches to earth buildings' research are encapsulated in Pearson's informative text on conservation, which was written 'from a practical, rather than scientific or academic, point of view' (Pearson, 1992, xv). Furthermore, a reliance on anecdotal or inferred knowledge relating to the deterioration of earth walls is reflected in the buildings' conservation work of Feilden (2003, 74), who, as Director Emeritus of ICCROM, suggested rather pseudo-scientifically that rain impact at earthen surfaces 'probably' re-orientates the clay plates and improves resistance. Houben, Balderrama and Simon (2004) also refer to the importance of developing techniques that dovetail with the key conservation principle of minimal intervention, the implication being that there remain gaps in knowledge that could notably improve conservation. The application of non-destructive scientific techniques is well established in relation to analysing historic artefacts (Janssens, 2005) and cultural heritage more generally (Artioli, 2010), however, becoming increasingly prominent over the course of the latter-twentieth century. Artioli (2010) has provided an extensive summary of the symbiotic relationship that has developed between studies of cultural heritage and materials science as a consequence of shared interest in the application of scientific techniques, despite custodians and scientists meeting from initially polar opposite perspectives.

Integrated scientific techniques have been used increasingly in the characterisation of historic earth building materials beyond Scotland. Brown, Robbins and Clifton (1979) used thin section microscopy, integrated with X-ray diffraction (XRD), particle size and scanning electron microscope (SEM) analyses, in assessments of weathering at three historic adobe structures in Arizona. This apparently novel approach is particularly noteworthy as a somewhat isolated early example of integrated scientific assessments of climate-related deterioration in earthen materials. Rosen (1986) provided an important step forward in terms of applying geoarchaeological approaches to the study of earth building materials' deterioration, whilst the use of laboratory apparatus for materials' characterisation have become more typical within the past decade. Materials from the iconic Bam Citadel, in Iran, have been subjected to mineralogical and micromorphological analyses with a view to differentiating between original and restoration materials found at the archaeological site of Kerman (Farpoor, 2003). Similar objectives have been realised in analysing materials at the Uch Monument Complex in Pakistan, with laboratory quantifications being augmented through the use of SEM and XRD (Bell and Böke, 2010). Nodarou *et al.* (2008) utilised micromorphology, neutron activation, X-ray fluorescence (XRF) and XRD to compare the material make-up of excavated mud bricks from Bronze Age East Crete with a view to determining sources of the raw soils used. These initiatives are of great value to the process of considered restoration, reflecting attempts at materials' replication through the characterisation of historic samples, but they add less to understandings of the underlying processes that have caused the initial deterioration of earthen building materials. It is this aspect of the application of the techniques referred to in this thesis that encapsulates the novelty of the integrated laboratory and *in-situ* fieldwork outlined in chapters 5 to 10. Furthermore, the methodologies utilised in this research are closely aligned to key research activities identified by UNESCO in its WHEAP Project Document (2012), including requirements for experimentation and laboratory-based analyses of materials in relation to water ingress and the effects of salts, alongside applied investigations at extant structures. The scientific investigations alluded to above are generally focused on either failed structures or archaeologically excavated sites. In contrast, it is the intention here to utilise a similar suite of techniques in the assessment of extant structures. Furthermore, the paucity of comparable research relating to less arid contexts such as that of northern Europe reflects a continued under-appreciation of the extent and significance of earthen building traditions within mainstream heritage discourses and thus, the value of exploring the utility of scientific applications to the assessment of Scotland's earth-built heritage.

1.5 Conclusion

This introduction has sought to provide a general overview of the interest in earth building in Scotland and the wider research arena within which this thesis sits. It has been the intention to offer explanations of some of the basic concepts integral to understanding unfired soils as building materials and how certain technical knowledge has been inherited through the millennia and was formalised in antiquity. The development of increasingly scientific approaches to understanding the earth-built heritage globally from the second half of the twentieth century provides an important backdrop to the latter part of this thesis, where the focus is turned to the results of field sampling and experimentation work using a range of integrated scientific techniques.

Historical significance

2. Global earth building

2.1 Introduction

Earthen buildings have been constructed globally for millennia (Weismann and Bryce, 2006), with aspects of universality to be found in many of the basic principles of application within the innumerable traditions that have existed among geographically and temporally disparate communities (Oliver, 1983). Archaeological excavation dates the oldest evidence for earth building to over ten thousand years before present, in line with the advent of civilised cultures in the Middle East (Hurd, 2011; Namdar *et al*., 2011). The architectural complexities achieved using earthen materials and the diverse environmental, social and spiritual contexts within which they have been deemed appropriate undermines perceptions of earth buildings as being little more than primitive dwellings raised and inhabited by those with limited options. This fissure between archaeological and historical evidence for the use of earth in higher status and urban contexts, and the development of negative perceptions in recent centuries or decades, depending on location, provides a theme running through earth building discourses. This provides challenges in terms of procuring evidence and removing the biases of inherited perceptions, particularly in relation to the vernacular experience of earth construction that is of most interest to this research.

There is a range of tests that can be used to determine soil properties, many of which are quite simple and can be conducted *in situ*, although the earth-built heritage and the traditions it embodies are the product of accumulated experience of using soils in construction over many generations. Indeed, there is an intangible cultural aspect to the earth-built heritage that is intrinsically linked to the fundamental properties of the materials used, with extant historic and traditionally-built structures embodying a huge range of spiritual belief systems across the world (for example, van Vuuren, 2008) and community structures that are often either under threat or completely lost. Familial, kin-based and social networks have formed the basis of earth-building projects across large parts of the globe whether for the purpose of erecting a simple family home or a centrally-administered structure of monumental proportions, often revolving around master-craftsmen whose knowledge was, and in some places still is, passed on through such ties.

Earthen building materials are hugely versatile and have been employed variously in plasters, mortars, flooring, roofing, water-proofing and oven-building, to name only a few applications. This thesis concentrates mainly on the use of earth as a principal walling constituent, however. Thus, the intention here is to provide an essential starting point for considering and contextualising the significance of earth building traditions through a basic understanding of the breadth of material applications and shelter types found worldwide, offering insights into the simultaneous variability and universality to be considered across the overarching field of interest. The following synopsis is therefore designed to fulfil this objective by introducing some of the pertinent themes that can arise from a wide survey of materials and building styles.

2.2 Materials and building styles

2.2.1 Subterranean and semi-subterranean earth buildings

Subterranean and semi-subterranean dwellings, whether entirely below ground or part-excavated covered shelters, can be considered the most fundamental of earth structures and are found across a range of environmental and climatic contexts. In China, the deep loess soils found in the Huang He River Valley were sophisticatedly excavated to provide dwellings for the people who established the civilisation named after the region (Jiyao and Weitung, 1990) and still today deeply-dug courtyards with barrel-shaped tunnel shelters running into the landscape can be found in rural areas. Similar practices are still found in North Africa, such as on the Matmata Plateau in Tunisia, for example, where berbers introduced subterranean dwelling practices prior to the arrival of Islam (Golany, 1988) (Fig. 2.1). Examples of excavated dwellings are found all around the Mediterranean basin, perhaps most famously in the Andalusian region of Guadix where contemporary interest and investment is ensuring the perpetuation of the tradition (Eugenia and Alessandra, 2011). In medieval Europe Hungarian pit-houses included a variety of dimensions and roof styles, which have been explored through ethnographic evidence and attempts at modern replication. Evidence attests to the great size of some of these ‘temporary’ structures of medieval date and the excellent thermal regulation they offered across great seasonal extremes in climate (Sabján, 2002). In New Zealand traditional Maori homes are noted as being sunken-floored with the excavated earth piled around the outside and roofed using bark to give protection from the elements (Howard, 1992).

Fig. 2.1. Subterranean dwellings such as those excavated by berbers in Matmata, southern Tunisia, offer respite from extremes of temperature.

2.2.2 Turf

Cut turf, taken from the uppermost layer of the ground and carrying an inherent structural integrity provided by root systems, is the simplest and most direct means of obtaining blocks of unfired material for building. Great diversity in the shapes, sizes and characteristics of cut turfs can be found in traditions across the world, as well as intra-regionally (Walker *et al*., 2006), depending upon the types of soils and grasses.

Turf is a material synonymous with the building traditions of northern Europe, ideally suited to the climate and environments of northern Britain and the Scandinavian world, and its use stretches back deep into prehistory in these areas. In areas of medieval Jutland structures were erected using a combination of turf and timber planks (Skov, 2001). Wilkinson (2009) has emphasised the complexity with which turf building traditions developed in Iceland, where the absence of alternative materials meant that such practices dominated until the late-nineteenth century. The preservation of this tradition into recent Icelandic history (Fig. 2.2) has provided insights into its use across other parts of northern Europe, including Scotland (Walker *et al.*, 2006). There is a deep history of craft in the choices of turf types in relation to purpose and the variety of tools used in their manipulation have been identified (Gailey and Fenton, 1970; Sigurðardóttir, 2008). Turf is known to be cut using specific tools in parts of central Asia, being allowed to dry before use (Fodde, 2009). Early-nineteenth century Australian records indicate the existence of turf-built Aboriginal structures, with large dwellings housing up to twelve people being made with timber formwork covered in turf (Howard, 1992) and Maori storage buildings were built using turf in pre-European New Zealand (Bowman, 2000). According to Buzás (2011) turf dwellings were synonymous with poverty in southern Hungary, a link that was increasingly made in Scotland over the course of the historical period. This rejection of turf was not universal, however, as sod houses proved to be popular during the nineteenth century in Australia and New Zealand, with encouragements being made to settlers to build in this manner based on the thermal qualities and cheapness of the material. In Australia, European and Chinese settlers alike imported their knowledge of building with turf and some examples having been shown to have survived for over a hundred years, although few have remained into the present day (Howard, 1992). This process was replicated in North America and the development in the later-nineteenth century of the sod house frontier in the midwestern United States was traced between 1886 and 1892 in the photography of Solomon D. Butcher (Turner, 1975). Turner attributed the development of this tradition to the absence of alternative building materials and construction tools beyond basic farming implements, yet also noted that sod-building remained popular into the twentieth century in Nebraska in spite of the arrival of the railways in the 1890s.

Fig. 2.2. Replica Icelandic longhouse, in Haukadalur, built using turf in the medieval tradition. Note the herring-bone arrangement of the turf blocks.

2.2.3 Earth and timber

Archaeological excavation attests that wattle and daub, whereby wet mud mixtures are applied to woven wattlework, was the original earthen building technique employed in Egypt, preceding the development of adobe construction, with evidence being found in sites dating to the Predynastic period (c. 5500 BC to c. 3100 BC) (Kemp, 2000). Contemporaneously in China, common dwellings were also being erected using woven, daubed stakes (Holmes, 2000). Wattle and daub traditions are found across the African continent, with a great range of additives and external finishes being used to aid the durability of the applied mud. This might include the use of dung, ashes or vegetable oils, the latter of which is said to serve as a water repellant (Kamamba, 1990). Ancient wattle and daub traditions have also persisted in rural Sri Lanka, alongside a great range of other earthen construction techniques including rammed earth, mud-mortared rubble and adobe (Nandadeva, 1990). Likewise, it is common to find daubed framework in Central Asia, whilst structural timbers with mud brick infill are built as a means of earthquake protection in Tajikistan (Fodde, 2009).

Wattle and daub was common throughout Europe, used both externally and in internal partition walls as far north as Scandinavia, where Viking Age examples have been excavated (Andersson, 2011). The prevalence of timber-framed buildings in Central Europe meant that clay-rich subsoils were widely utilised as a means of filling the spaces between structural timbers, particularly agricultural buildings in the Netherlands, for example (Rijksdienst voor het Cultureel Erfgoed, 2010). In Poland and Hungary concerns in the seventeenth and eighteenth centuries relating to the over-exploitation of woodland resources for building led to an increase in half-timbered construction methods. Typically, either daubed wattlework or mud-filled studwork occupied the spaces between the main timbers (Fig. 2.3), although mass earth techniques are also known to have been used for this purpose (Kelm, 2011; Buzás, 2011). Similar concerns in Germany extended to the implications of fire-risk posed by fully timber-constructed buildings and led to the publication of standards for earth building practices from the sixteenth century (Schroeder, 2011).

Fig. 2.3. Dilapidated agricultural building near Siedleçin, in Lower Silesia, Poland, exhibiting a range of building materials and methods, including timber frame and daubed timber infill.

Mud was used by Aboriginal people in Australia to plaster beehive structures, particularly in the north and wattle and daub was used by the earliest white settlers upon arrival (Moor and Heathcote, 2002), including Germans who introduced 'fachwerk' (Howard, 1992). Such methods provided a useful short-term means of erecting shelters in New South Wales, whilst timber frames with panels of daubed poles were used to build a variety of community buildings as settlement took hold. Likewise, in New Zealand both temporary shelters lasting only a year or two and such buildings as the first government house were constructed using daubed wattles and poles. Italians and Germans also exported wattle and daub and adobe-filled timber frame building practices during the nineteenth century when populating the Blumenau Colony in Santa Catarina, southern Brazil (Kanan, 2000), although a pre-existing tradition of wattle and daub building existed in South America. Notably, Spanish colonists adopted the pre-Columbian tradition of quincha, a method of wattle and daub work indigenous to Peru, in the mid-seventeenth century, as a means of incorporating seismic resistance in major buildings such as the Church of San Francisco in Lima (Camilloni, 2003).

2.2.4 Mass earth or monolithic earth walling techniques

Monolithic earth walls of varying type are here referred to under the umbrella term of mass earth. The materials used and means of construction employed within this bracket mean that rammed earth, adobe and cob walls are very different in their characteristics and performance. They are grouped together, however, on account of all being methods by which solid earth walls can be vertically raised without recourse to the addition of stone or timber for structural support. It is also worth noting that such techniques can be combined and the use of pre-dried mud blocks is typical in the restoration of historic mudwall buildings in Scotland, such as the Logie Schoolhouse in Angus (Fig. 4.3) and the Old Schoolhouse in Cottown, Perthshire (Chapter 7).

2.2.4.1 Rammed earth

Rammed earth walls are formed by laying soil material, sometimes with organic fibre or aggregate, within removable timber formwork, with the name referring literally to the process of compaction using ramming implements. This method reduces the reliance on clay to act as a binding material in the same way as in cob or adobe. The high level of density achieved in rammed earth walls (around 1900 to 2200 kg/m^3 (Keefe, 2005, 43)) relates directly to the material characteristics of soils used, levels of moisture present during construction and the force applied during compaction, with historic examples having been shown to be similar to modern equivalents (Arango Gonzalez, 1999; Maniatidis and Walker, 2003). The technique has been employed across social and architectural spectra, originating independently in China and the Mediterranean (Jaquin *et al.*, 2008), before spreading to the Americas and Australasia through European colonisation. Massive rammed earth walls in China, as thick as 13 m at the base, can be dated back in excess of 4000 years and others built within the last thousand years are as thick as 18 m. There is a strong tradition in China of building defensive structures in rammed earth, with city walls built in this way in numerous areas over many centuries and multi-storeyed fortified family dwellings constructed during the first millennium AD (Jaquin *et al*., 2008). Large sections of the Great Wall were constructed using rammed earth and adobe during the Qin (221-206 BC), Han (206 BC-AD 220) and Ming (AD 1368-1644) dynasties (Jiyao and Weitung, 1990), as were many other protective walls and fortified farms built at a familial level in the first millennium AD that still stand in their thousands. Many extant structures are still to be found along the route of the Silk Road in both urban and rural contexts (Xudong, Luixiong and Haiying, 2005). In Tibet rammed earth has been used to build loadbearing walls to two-storeys, with flat roofs constructed in the same fashion on top of timbers and finished with waterproofing clay (Chayet, Jest and Sanday, 1990). Rammed earth is found across much of Central Asia (Fodde, 2009), with soils of various type being compacted in wooden shuttering and fibrous material added at intervals. Fodde asserts that the rammed earth method provides increased protection against the capillary rise of water due to the absence of pore space within the walls.

The origins of rammed earth in Europe have been attributed to the Phoenicians (Jaquin *et al.*, 2008), whose great expansion across the Mediterranean occurred from c. 1200 BC, although Illampas *et al.* (2011) describe circular dwellings in Cyprus being built in this way as far back as 8500 BC. Again, archaeological evidence points to the propagation of the technique over the following centuries. Roman shuttered earth walls built on stone foundations have been excavated at Verulamium (St Albans, Hertfordshire) (McCann, 2004). Across southern Europe and North Africa, the need for fortification following Muslim expansion led to the construction of rammed earth castles in Spain, such as at Alhambra, by the end of the first millennium AD (Jaquin *et al.*, 2008) and the 1600 m long Murallas de Niebla fortification, built in the twelfth century in Huelva (Delgado and Guerrero, 2005). Links between southern Europe and North Africa are emphasised in the fortified residences – kasbas – found in the south of Morocco (Fig. 2.4), where rammed earth and adobe were used in conjunction to create highly multifunctional structures (Michon, 1990). Southern France has a long history of rammed earth construction and archaeological excavation has unveiled such walls dating back to the third century AD (Houben and Guillaud, 1994), ultimately providing the platform for its later transfer to North America and Australasia after being re-popularised in Central Europe during the eighteenth and nineteenth centuries. A range of rammed and shuttered earth wall types are known across regions of Hungary, with the ramming of brick-sized clay balls being said to be a precursor to more typical rammed earth techniques where clay-rich soils free of large aggregates were thrown between clamped timber boards and compacted (Buzás, 2011). Examples of permanently-shuttered rammed earth walls are also known from across Hungary and Poland, where woven wattles provided the internal and external skins, which were then whitewashed post-construction. This is said to have been employed in castle-building originally, before becoming a feature of the vernacular domain. Amendments to the typical earth building materials could include lime or peat (Kelm, 2011) and reinforcement between the shuttering and earth with wattles and reeds are also known (Cseri and Buzás, 2000). The palace at Tarchomin in central Poland demonstrates the fine style that could be achieved in conjunction with levels of durability offered by metre-thick walls (Kelm, 2011).

Fig. 2.4. The ksar (walled city) of Ait ben Haddu in the valley of Draa river, close to the city of Ouarzazate, Morocco. The city contains several kasbas and holds UNESCO World Heritage Site Status (Photo credit: Pablo Muñoz Carballeda).

François Cointeraux is credited with bringing the merits of rammed earth building practices back into particularly strong focus. Hailing from Lyon, where the technique was known as *pisé de terre*, Cointeraux devoted himself to developing rammed earth building methods and produced over seventy pamphlets on the subject from the mid-1780s. Although Cointeraux was neither the first nor only person in eighteenth century France to extol the qualities of pisé, his efforts stimulated a wider interest within and beyond contemporary France (Cody, 1990; Jaquin *et al*., 2008; Young Lee, 2008). Cointeraux's work, written in the spirit of Enlightenment thought, added aspects of materials science, technological development and artistic expression to vernacular building and reproductions of his work appeared across Europe, including Italy, Germany and Britain, where the architect Henry Holland promoted its adoption through the Board of Agriculture. Young Lee (2008) cites economy, durability and patriotism as motivations for the encouragement of the common people to adopt rammed earth building during the politically-charged milieu of late-eighteenth century France, although she notes that the method was never accepted as appropriate for major urban projects and remained intrinsically linked to rural agricultural contexts. Nevertheless, pisé was deemed to be a democratic building method, producing healthy, attractive and inflammable dwellings from, in contrast to timber, an abundantly available and free resource. Inspired by Cointeraux, rammed earth became commonplace in Germany, where multi-storeyed buildings of nineteenth century date remain. Jacob Wimpf, for example, raised rammed earth factories and, in 1837, a rammed earth building of five storeys on one side and three on the other was constructed on a mountain-side in Weilburg, where it still stands. In the first quarter of the nineteenth century, the Lippe-based architect Wilhelm Tappe developed, with limited success, dome-shaped dwellings built using unfired earth bricks with a view to providing cheap, durable and easily constructed homes for the poor. The thermal properties of massed earth were also recognised in this period, with Christoph Bernhard Faust (1755-1842) being credited as 'one of the co-founders of the concept of the "Zero Energy House"' (Güntzel, 1990, 63). Industrial buildings of multiple storeys were built also in mass earth in ninetenth century Austria and there remained a professional audience willing to consider the use of earth in construction in the first half of the twentieth century. A decisive break with traditional building practices is said to have taken place in the second half of the twentieth century, however, with changes to rural society and technological progress impacting upon public perceptions of historic earth buildings which became increasingly scarce (Maldoner, 2007). The technique was also taken to Scandinavia where it was used until the introduction of Portland cement in the late-nineteenth century (Jaquin *et al.*, 2008). Pisé techniques were employed in 1790s Russia through a somewhat circuitous route, with architect Nicolai L'vov enlisting Scottish expertise to assist in the building of a range of new pisé structures that included elements of traditional building practices imported with these Scotsmen. In 1799 the chief designer amongst these recruits, Adam Menelaws, even became the architect of the newly established School of Earth Construction, just outside Moscow, although this venture died along with L'vov in 1803 (Makhrov, 1997). This episode clearly demonstrates an awareness and knowledge of modern earth building techniques in late-eighteenth century Scotland.

The virtues of rammed earth were also recognised beyond European shores and interest in pisé was transmitted to the neo-Europes of North America and Australasia in the early- to mid-nineteenth century. Stephen Johnson of New Jersey, who regurgitated the work of Cointeraux and Holland in his own terms in the first decade of the nineteenth century, is attributed with introducing rammed earth to the eastern United States with a view to selling manuals to farmers on newly-settled land (Cody, 1990). This ignited an interest amongst agriculturalists that was maintained over the following decades up until around 1870 and also led to the development of a variant called tapia, which used shells, small stones and lime as the primary constituents. It should also be noted that Chinese migrants took their rammed earth methods to these newly-colonised lands, with populations growing in conjunction with mineral extraction activities. Rammed earth proved to be the most popular means of earthen construction in nineteenth century Australia, being encouraged in newspapers and pamphlets (Moor and Heathcote, 2002), and extant structures from this period can still be found with evidence of a great variety of material amendments, including the addition of boiling fat (Howard, 1992).

As already mentioned in reference to Clough Williams-Ellis, there was a revival of interest in earth construction in the United Kingdom in the years preceding and following the Great War (Swenarton, 2003). The influential owner/editor of the Spectator magazine, and father-in-law of Williams-Ellis, St Loe Strachey, was attributed by his contemporaries as the originator of increased interest in earthen materials from the turn of the twentieth century as a solution to the dearth of rural housing and the inhibiting costs involved in rectifying the situation. Government promises to build suitable homes for servicemen on their return from the Great War, together with plots of land in rural locations, provided further stimulus for reconsidering earthen techniques, which Williams-Ellis eulogised about in his 1919 publication. The most tangible result of government interest was the construction of thirty-two experimental houses in Amesbury, Wiltshire, by the Board of Agriculture, with six being built with rammed earth (including one of chalk and another of chalk-cement) and two with cob (Jaggard, 1921). Although these experimental dwellings were raised with success, the 'enthusiasm of revivalists' was not enough to encourage the wider application of earth building (*Department of Scientific and Industrial Research Building Research Board*, 1922, 1) and the economic incentives quickly dissipated (Swenarton, 2003). Testifying to this, the Department of Scientific and Industrial Research Building Research Board's report of 1922 asserts that 'it cannot be claimed that any considerable urban housing scheme could be satisfactorily carried out in this country in either *pisé de terre* or clay-lump. Mass cob is out of the question' (Department of Scientific and Industrial Research Building Research Board, 1922, 1).

2.2.4.2 Mud brick or adobe

Mud brick, commonly referred to as adobe, remains the most widespread earth building method around the globe. The etymology of the universally recognised term is often given as the translation of the Arabic *tub* into the Spanish *adobe*, although the deeper Egyptian roots, where mud brick was known as *djebet*, are often overlooked as the precursor to the Arabic name (Kemp, 2000). Kemp suggests that adobe construction prevailed in Predynastic Egypt in preference to fired brick, which is only occasionally seen in the archaeological record. In contrast to the predominantly rural vernacular contexts in which earth building techniques were employed around medieval Europe, entire cities have been built in Central Asia, the Middle East and Africa for centuries or even millennia using unfired earth bricks. In Libya, for example, 600 historic adobe-built cities remain extant, with the material choices and urban designs being tailored in response to the environmental and social contexts germane to the region (Abufayed, Rghei and Aboufayed, 2008) and the Bam Citadel in Kerman, Iran, is regarded as the largest earth-built monument in the world (Farpoor, 2010). Likewise, many cities in Yemen are typified by iconic mud brick towerhouses, such as in the Hadhramaut region for example (Jerome, 2000), where the river valleys are flanked by cliff-top conurbations with blocks rising to ten storeys, only one of which is built each year. This pattern of settlement allows the maximisation of agricultural land, provides inherent protection from flooding in the valley and also served defensive functions during periods of conflict (Jerome, Chiari and Borelli, 1997). The stone-walled 720 ha area of Great Zimbabwe, which existed as a vibrant city between c. AD 1200 and 1500, was littered internally with mud brick dwellings and typified an architectural tradition that spread across much of the southern third of the African continent (Matsikure, 2000). In Peru, the city of Chan Chan (Fig. 2.5), capital of the Chimu kingdom from the ninth to fifteenth centuries AD, grew to be one of the largest pre-Hispanic settlements in the Americas and was predominantly built with adobe and large mud blocks. The Peruvian earth building tradition has persisted into the present, with 60% of the population estimated to having been dwelling in earthen homes in the early twenty-first century (Houben, Balderrama and Simon, 2004). In a European context, mud-brick buildings in Calabria, Italy, are known to rise up to five storeys and treatises of the fifteenth century detailing the use of adobe have been noted (Fratini *et al.*, 2011). Adobe is said to have been the most popular form of earth building in late-nineteenth century Hungary (Buzás, 2011), with variety in materiality and dimensionality apparent across the regions in which it was employed. Mud bricks were also used in conjunction with mud mortar throughout much of Cyprus to build variously-designed structures until the mid-twentieth century (Illampas *et al.*, 2011).

Fig. 2.5. The UNESCO World Heritage Site of Chan Chan, the capital of the Chimu Kingdom in north western Peru (c. 900 to c. 1470) and largest pre-Columbian city in South America.

Mud brick building in Mali has been well documented, partly as a result of the *10th International Conference on the Study and Conservation of Earthen Architectural Heritage* being held there in 2008. The iconic Friday Mosque in the World Heritage-listed town of Djenne, was built in 1907 using the fourteenth century Jingereber mosque of Timbuctoo as insipiration (Bourgeois, 1989) and serves as a living example that encapsulates aspects of monumental and vernacular earth building traditions the world over. The importance of regular maintenance and community collaboration are demonstrated in the annual application of mud mortar to the exterior of the building for protection during the rainy season. Mud masons also continue to operate around Djenne within professional structures dating back to the Mali Empire period of the thirteenth to early-fifteenth centuries that have ensured a continued respect for mud brick construction locally and negated the pressures for formal conservation that are prominent in locations where earth-building traditions have been lost (Marchand, 2008). Around much of Asia there is also a long history of earth building projects being managed under the direction of master craftsmen, as testified to in Indian documents from the middle of the first millenium AD and in preparatory sketches applied to walls at the site of Penjikent, in Tajikistan (Fodde, 2009).

Fig. 2.6. An example of mud brick construction at the community scale: the old village of Chebika, western Tunisia.

Fodde has noted the suitability of the prevalent loess soils in Central Asia for construction with mud bricks, emphasising the great local variety that exists in terms of their shape, size and application. Hand-moulded examples dating from the Neolithic have been excavated in this region, providing the earliest evidence for a building tradition that is maintained into the present. The city of Shimkent in Kazakhstan embodies a 2500 year-old mud brick tradition (Hurd, 2011), and it has been estimated that some 60-80% of dwellings across the region as a whole are still of unfired earth (Fodde, 2009). Fodde attributes the absence of fibrous additives to the well-graded nature of the loess, which inhibits shrinkage upon drying. A wide variety of ancient earthen structures are known in Central Asian countries, ranging from the humblest dwellings to monumental city walls or sophisticatedly-designed palaces and domed mausolea. Barrel vaults are also widely found, dating from the ninth century at the Qir Qiz Palace in Uzbekistan, for example, and allowing for houses of up to 10 m high to be built in Tajikistan (Fodde, 2009).

Fig. 2.7. The Huacas del Sol y de la Luna (Pyramids of the Sun and the Moon) were monumental adobe constructions of the Moche culture, which flourished in north western Peru between c. 100 and c. 800. Top: the Huaca del Sol, photographed from the approach to the Huaca de la Luna, was one of the largest pre-Columbian structures in South America. Like the Huaca del Luna, the pyramid was built using mud-mortared adobe and measured about 345 m x 160 m x 30 m prior to being damaged in the seventeenth century. Middle, left: extant walls within the Huaca del Sol. The pyramids grew over many generations, with original walls providing internal structure when new external walls were added. Middle, centre left: Ornately decorated walls that were buried within the structure over time. Note the deliberate removal of the central icons within the design of the upper wall. Midlle, centre right: El Mural de los Mitos (The Mural of the Myths), Huaca de la Luna. Middle, right: façade of the most recent exterior wall of the temple within the Huaca de la Luna. Bottom: adobe blocks excavated from within the Huaca del Sol, showing a wide variety of makers' marks.

Mud bricks are known to have been given identification marks during production from up to five-thousand years ago in Iraq and Iran (Fodde, 2009). In Egypt there was a strongly administered and intensive production of mud brick between the Eighteenth and Thirtieth Dynasties (c. 1550 BC – 343 BC), with official stamps perhaps used to donate the place in which transported bricks originated (Kemp, 2000). Great production yards were noted outside Yemeni towns by conservators in the late-twentieth century, with labourers capable of producing 500 bricks each per day (Jerome, Chiari and Borelli, 1997). Such traditions in the Arabian peninsula, together with religious, economic and social influences, resulted in a somewhat democratic urban aesthetic, with the outward appearance of dwellings appearing standardised once built under the central administration of master craftsmen (Saleh, 1998). A great array of personal makers' marks can be seen on bricks extracted from the Huaca de la Luna, near Trujillo in Peru (Fig. 2.7), somewhat reminiscent of the masons marks on dressed stones in the castles and cathedrals of medieval Europe. The development of earth building techniques to carry seismic resistance occurred from an early point and mud brick is still used within timber framework in Peru as a means of building structures resilient to earthquakes. Examples of earthquake-resistant mud brick construction are found elsewhere around the globe, with reeds being added between alternate layers of mass earth and mud bricks in structures dating to centuries BC for this purpose in Central Asia (Fodde, 2009).Traditional adobe structures in Macedonia, including an early-twentieth century two-story structure near Skopje, have been noted for their seismic resistance (Sumanov, 1990). Similarly, mud bricks were employed in the city walls of Nicosia in Cyprus, designed in the mid-sixteenth century, as a means of cushioning the blows suffered during attacks (Illampas *et al.*, 2011).

Adobe construction was introduced to New York State from the 1830s, following the influence of English publications encouraging the building of rural dwellings in clay lump (Chapter3; 3.3.1.2) and perhaps the skills imported with settlers themselves. Various experimentations and publications were made in the region, with these being influenced by journals emanating from Toronto, where adobe also proved to be popular. Although the wide social acceptability of adobe is reflected in valuations of homes that ranged between $100 and $15,000, the building technique began to fall out of favour amongst commentators as early as the 1850s (Pieper, 1990). Following the amalgamation of the south west into the United States adobe was used extensively in the settlement and control of the region. Garrison (1990) has identified three major phases of adobe building, the first of which borrowed heavily from pre-existing Native American and Colonial Spanish traditions as communities were built with appropriate consideration of the local environmental context. From the 1880s increasingly available industrial products, including timber and lime, were incorporated into adobe structures, particularly those built by the military. In the first half of the twentieth century there then followed a return to architectural styles more akin to the traditions of the region, but with the addition of cement, concrete and steel alongside the adobe walls.

Fig. 2.8. Different types of earthen construction can be found used in conjunction in boundary walls around Peru. Left: massive earth blocks sit atop alternating layers of smaller-sized adobes. Right: monolithic walling topped with mud-mortared adobe. Note the undercutting at the base of the wall.

2.2.4.3 Cob

Cob building techniques were employed in Central Asia from at least the pre-Islamic period and were predominantly found, as they still are today, in rural locations, often in combination with mud bricks. Defensive walls could be built to heights of over 6 m, often studded with towers at regular intervals, and as wide as 8 m, such as those dating from the ninth century that surround the city of Qhulbuk, Tajikistan. Although straw is generally not used the methods of construction would be recognisable across time and space, with clay-rich soils being watered and mixed by foot before being laid in lifts of varying height atop stone foundation walls (Fodde, 2009). In the American Southwest people of the late Mogollon and Anasazi cultures (c. 1200-1400) built variously sized multi-room settlements, or pueblos, in a way akin to cob, raising walls typically 20-30 cm thick in courses by hand using puddled clay with a high calcium carbonate content that set hard upon drying (Kirkpatrick, 1990). In Casa Grande Ruins National Monument, Arizona, the Great House was also constructed in the same manner in c. 1300-1450 and remains a monument to the grand architecture and social organisation of native populations in the region (Matero *et al*., 2000). In India, tribespeople continue to build cob walls by hand, laying three to four courses of elongated wet mud blocks before smoothing to fashion a uniform wall face. Although usually short-lived these simple structures are another example of earth buildings capable of withstanding seismic activity (Joshi, 2008). A similar process of cob building is retained in northern Yemen, with wet spheres of mud being laid in courses and continually smoothed during the construction process, although this technique has been applied to monumental city walls as well as in the vernacular context (Marchand, 2000).

Monolithic earth buildings with walls constructed in multiple lifts of clay-rich subsoil first wetted and mixed with fibrous material are known across various regions of Europe (Watson and McCabe, 2011). They were prevalent in central Europe from at least the Middle

Ages and archaeological evidence in Germany suggests the existence of such buildings as early as the eighth century (Güntzel, 1990). Güntzel has proposed that early medieval construction using massed earth was often carried out as a positive choice among builders in Germany, with the profusion of timber resources that still abounded around this time indicating a preference for monolithic walls built with clay-rich subsoils. This view is supported by Ziegert (2000), who emphasises that cob construction was the most commonly found method across a large area of central-eastern Germany until the late-nineteenth century, attributing this to a lack of timber resources and the suitability of the deep loess soils. Cob construction methods were consistent across social contexts, as well as between dwelling and agricultural buildings, and sometimes incorporated with a second storey of half-timber work. Archaeological excavation has revealed earth buildings in Austria dating to 4000 BC. Evidence for historic mass earth contruction typically follows patterns related to the availability of alternative materials and the status of those peasant populations who built and lived in vernacular dwellings (Maldonar, 2007). Documentary sources discussing cob building date from the first decade of the seventeenth century in France, where the technique is called bauge and can be traced across regions including Brittany, Normandy, Poitou, Cotentin, Bessin and Vendee (Patte, 2004), with notable similarities to the cob building tradition of Devon (Keefe, 1992). Furthermore, the familiarity and quality of French practices to British eyes was reflected in the testimony of the agronomist Arthur Young in 1788:

They build in this country the best mud houses and barns I ever saw, excellent habitations, even of three storeys, and all of mud, with considerable barns and other offices. The earth (the best for the purpose is a rich brown loam) is well kneaded with straw; and being spread about four inches thick on the ground, is cut in squares of nine inches, and these are taken with a shovel and tossed to the man on the wall who builds it; and the wall built, as in Ireland, in layers, each three feet high, that it may dry before they advance. The thickness about two feet. They make them project about an inch, which they cut off layer by layer perfectly smooth. If they had the

English way of white washing, they would look as well as our lath and Plaister, and are much more durable. In good houses the doors and windows are in stone work (Patte, 2004, 5-7).

Mud walls were built in the using the same methods in the Carpathian Basin, with pitchforks used to place each lift of material, as well as by laying semi-dried balls of the building material before trimming once a wall of requisite height was achieved (Cseri and Buzás, 2000).

A rather idiosyncratic example of the transfer of the European cob tradition can be found in the state of Victoria in Australia, where a mid-nineteenth century two-storey structure known as Bear's Castle still stands. This turreted, square-plan building was raised by men from Devon using vernacular knowledge acquired before emigration to create a faux-keep at the apparently flippant request of reservoir manager Thomas Bear (Howard, 1992). Cob building was particularly popular during the mid-nineteenth century settlement of New Zealand, particularly on South Island where the soils were considered highly suitable and the abundant tussock grasses provided a natural source of fibrous material to add to the mixture. Extant examples of two-storeyed cob houses built by wealthy merchants in the 1840s and 1850s are testament to the regard with which the method was held and to the quality of building that could be achieved (Bowman, 2000).

Cob building is addressed more fully in the following chapters, where it is mostly referred to as mudwall, firstly in reference to evidence from across England, Wales and Ireland as a means of contextualising the subsequent discussion of Scotland that is elucidated in the following chapters.

2.3 Conclusion

This discussion has sought to introduce the importance of perception to the historic and contemporary assessment of earth building materials and methods. There are both tangible and intangible aspects of earth building that are of great value in heritage terms, particularly when consideration is given to the significance of inherited knowledge that is embodied in the maintenance of vernacular building methods and the sense of community involvement that this relates to. Similarilarities in earth building traditions that have developed independently around the globe, as well as those that have been successfully exported across thousands of miles, emphasises the universality of techniques despite the fundamentally local character of specific traditions that are explained by the geology and soils inherent to an area. The prevalence of monumental and urban earthen architectures across a range of temporal and cultural contexts also highlights an important crossover between vernacular and refined approaches to construction.

Building with earth as a primary structural constituent is highly sustainable, offering the potential to avoid the extensive use of timber or imported materials at times or in places of pressure on such finite resources, but its relative inefficiency can be seen as aprimary driver in its disappearance from the landscapes of developed regions. Earthen materials were not necessarily used due to a lack of alternative options and could indeed be deemed appropriate across a range of functions and social contexts. The rejection or acceptance of earth building has been variable throughout history around the globe, depending on economic, technological, environmental, cultural or social factors. The late-eighteenth and early-nineteenth centuries saw a revivial of interest in earth building techniques in central and northern Europe, prompting innovation in application and the development of architecturally-designed earthen structures, with *pisé* or adobe often regarded as a means of promoting better public buildings. Although this trend permeated to the United Kingdom, concurrent debates over the quality of housing were fuelled by the desire for 'improvement' and the replacement of vernacular materials, which is dealt with in greater detail in relation to Scotland further on.

The themes outlined in this chapter provide links between earth building traditions globally, whether based in arid-hot or wet-temperate climates. Appraisals of historic earth building practices cannot be removed from local environmental contexts. Nonetheless, the utility of considering traditions across the globe, even with a great deal of attention placed on hot-arid regions, gives initial elucidation to themes that emphasise the universality of the materials and methods involved and embeds the history of Scottish earth building within an international framework that highlights the value of extant structures to organisations such as the ICOMOS. As noted in the glossary, "earth-built" is a convenient umbrella term and the great variety with which the term earth-built heritage may be referred has been seen through the opening discussion. This, for reasons already offered, is an invaluable starting point, but given the breadth of construction materials and methods encompassed it is important that this thesis offers greater focus within the Scottish context. Therefore, the following chapters concentrate primarily on wet method, mass earth construction techniques once prominent across various parts of the British and Irish islands.

3. Earth building in England, Wales and Ireland, with a focus on mudwall techniques

3.1 Introduction

Wet method earth building traditions were common throughout England, Wales and Ireland prior to the twentieth century and aspects of continuity between them serve as a useful point from which to provide comparison with those found in Scotland. Climatic reasons have dictated that earthen structures have not been as prominent in the United Kingdom as those parts of the globe with more arid environments (Warren, 2000), where earth building traditions have persisted and can be found equally in monumental and vernacular architectures. Furthermore, a set of environmental, economic, technical and cultural circumstances dictated the cessation of vernacular earth building traditions and the removal of the majority of the stock of historic massed earth structures from British and Irish landscapes in most areas. This is with the conspicuous exception of cob, however, which still abounds in south west England. Pre-conceived ideas about preferred construction practices whereby clay was the building material of last resort used only where alternatives were unavailable (Penoyre and Penoyre, 1978) and the relative lack of surviving structures has encouraged contemporary presumptions as to the subordinate standing of historic earth buildings. As suggested by Longcroft (2006, 61), however, 'absence of evidence does not necessarily imply evidence of absence.' Indeed, a growing body of historical and archaeological research attests to the relative proliferation of deep-rooted earth building traditions across many regions of the United Kingdom and Ireland and not just those enclaves where survivors are found.

3.2 The study of vernacular and historic earth building in England

The study of vernacular building traditions in English historical discourses has been heavily influenced by two theories that have transcended the sub-discipline, Hoskins' theory of the Great Rebuilding and Brunskill's supplementary concept of the Vernacular Threshold. Hoskins (1953) outlined that a 'revolution' in the housing of the English nation occurred between c. AD 1570 and c. 1640, based upon extant structures and documentary evidence, thus encouraging linear explanations of building development with distinct chronological boundaries between obsolete and innovative methods. This account attributed the growing trend for privacy, influenced by housing developments on the continent, as a precipitant for the replacement or remodelling of medieval peasant dwellings from the later sixteenth century. Hoskins also deemed improved health and population increases to be primary factors, although with some circularity in terms of determining whether these were initially a cause or effect in relation to improvements to the building stock. Johnson (1993) noted that criticism and revision of the Great Rebuilding was not forthcoming until the 1970s, suggesting that initial acceptance, in spite of notable gaps in, or absence of, evidence used by Hoskins, is explained by how well it fit into prevailing contemporary theories of English social history in the build-up to the Civil War period. Although Hoskins acknowledged the possibility of the northernmost counties experiencing the Great Rebuilding from the end of the seventeenth century, Brunskill (2000 [originally published 1971]) sought to shift the boundaries of the theory to include any point between the mid-sixteenth and eighteenth centuries, depending on the vagaries of local economies, cultures and resources. Brunskill surmised that a combination of increased availability of cheaper, superior building materials together with increased security of tenures encouraged rural communities to invest in relatively expensive building projects. These factors led to the abrupt discontinuation of centuries-old typologies in the surviving record, with the point at which this occurred in a given locality being termed as the 'Vernacular Threshold'. The influence of Brunskill's theory, which explains developments in architecture in terms of an inevitable progression away from the vernacular, is apparent in established views as expressed in the British Standard (1998) *Guide to the principles of the* *conservation of historic buildings*, and places emphasis on the availability and utilisation of alternative permanent materials (Brunskill, 2000).

The notion that vernacular buildings of medieval origin were doomed to extinction as a result of their material impermanence is one that has pervaded much of the discussion on vernacular building history. Salzman (1952) recognised the importance of earth building materials to the erection of dwellings by the rural majority in medieval England, yet devoted negligible space to discussing this. The one extended passage that he provides on the subject exemplifies typical perceptions of vernacular dwellings and their inhabitants, stating that

‘The primitive huts of the poorer peasantry, constructed by their owners with walls of sods, trampled earth, or mud-plastered wattles, and roofs of unshaped poles covered with turf, heather or straw, may seem hardly to come within the category of building’ (Salzman, 1952, 187).

Likewise, Sheppard (1966, 22) asserted that

‘Virtually all medieval houses were simple and relatively impermanent structures erected by household or communal effort and using for their walls either rough timbers and mud or stone rubble’.

Somewhat contrary to the theory of the Vernacular Threshold, however, Brunskill (2000) acknowledged that structurally ‘vulnerable’ mudwalls were retained well into the nineteenth century even in areas with apparent access to ‘superior’ building materials. It may be inferred from this that earthen materials were not always deemed an inferior choice and that judgements on the inferiority and impermanence of earth buildings are a reflection of twentieth-century detachment from traditional building materials and methods. This point is given credence if one accepts the stigma that words such as peasant or tenant have come to be associated with in contemporary explanations of medieval life. There is ample evidence to show that peasants would invest in constructing substantial buildings with crucks, stone plinth walls and sometimes tiled roofs, and craftsmen such as carpenters are also known to have been employed alongside unskilled labourers in peasant building projects (Dyer, 1986).

The logic of judging exponentially older vernacular structures based on the numbers by which they have survived into the present has been questioned by Dyer (1986), who has emphasised that the current existence of any medieval peasant buildings should be deemed exceptional. This calls into further question the reliance on survey as a means of historical enquiry that has been so relied upon in appraisals of vernacular building (Fig. 3.1), particularly in relation to Scotland's earth buildings. Indeed, the same author concurrently suggested that excavated evidence from the multitudes of lost structures could be used more objectively as proof of their durability. Currie (1988) contributed to this debate on similar lines, questioning the misleading emphasis placed by students of vernacular building history on evidence gleaned from the patterns of surviving (versus non-surviving) structures. As pointed out by Hurst in 1971, non-surviving excavated rural structures are generally found in abandoned villages where the reasons for the demise of the buildings related to wider social and economic circumstances rather than their material and structural properties (Beresford and Hurst, 1989). This leads one to conclude that perceptions of historic buildings based on their survival into the present neglects the eminent possibility of random distribution of surviving vernacular buildings as a result of chance over time, rather than an inherent superiority over those which have been lost. Brunskill (1962) had already picked up on this point in relation to his surveys of earth building in Cumberland, noting that apparent patterns of distribution are unquestionably skewed by the rapid loss and meagre remains of abandoned mudwall structures. Dyer (1986) also apportioned blame for the perpetuation of appraisals of pre-Modern vernacular peasant buildings as 'flimsy' or 'impermanent' in the descriptions of site contexts by archaeologists, suggesting that conventional wisdom of the time accepted that such structures were replaced wholesale upon the advent of conditions that facilitated the building of durable alternatives.

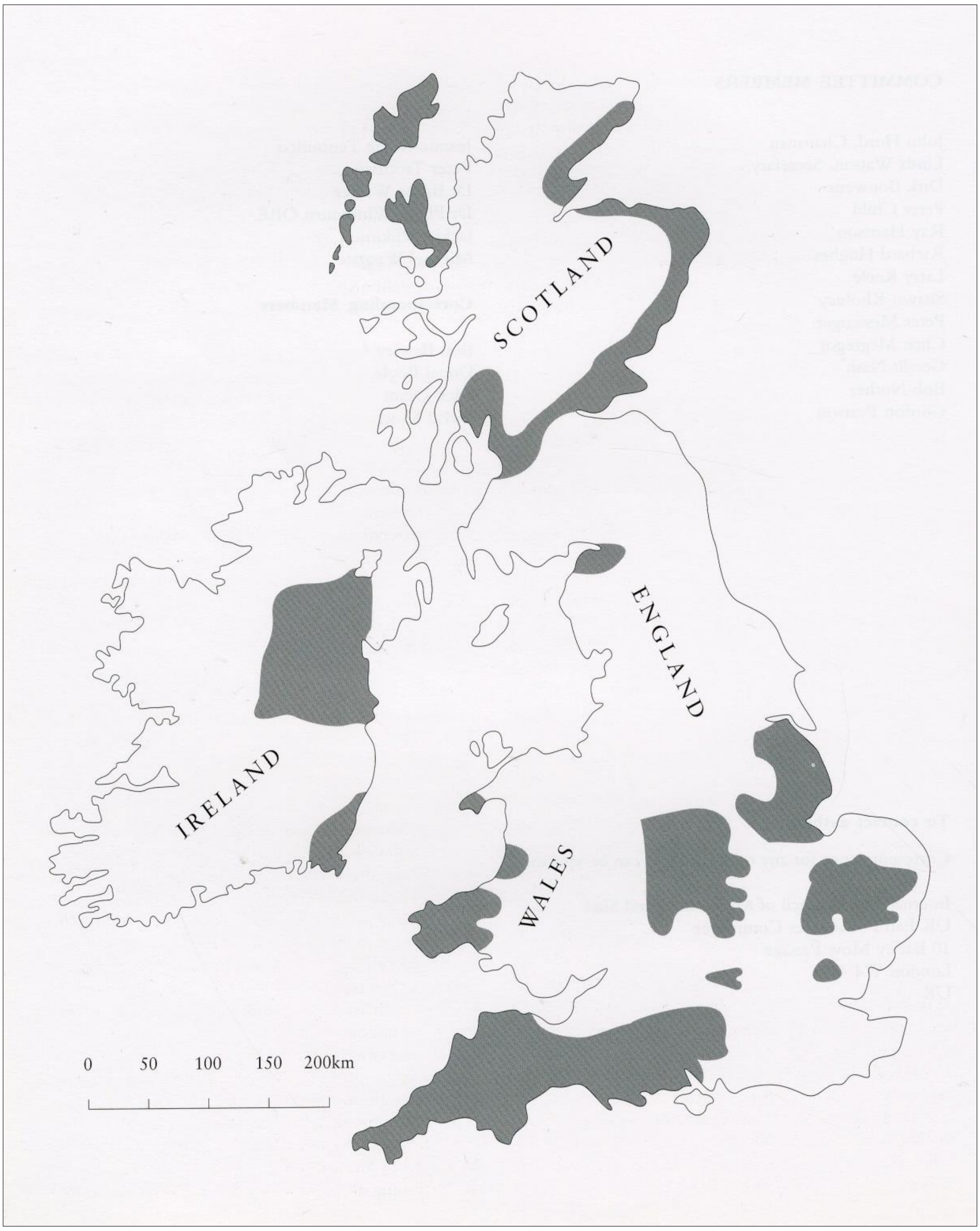


Fig. 3.1. Map depicting the ‘main centres of earth building in Great Britain and Ireland’, as shown in Hurd and Gourley (2000). In reality, however, the map indicates the extent of research relating to earth building practices used for the *Terra Britannica* volume from which it is taken, offering useful insight as to some of the most well-known concentrations. Whether inadvertently or not, however, the map suggests that earth building was historically confined to specific enclaves and demonstrates the inheritance and perpetuation of ideas as to the limits of earth building practices.

Wrathmell (2001) has contributed to the reassessment of medieval vernacular dwellings, using archaeological evidence to argue that such buildings could be designed with the capability to last for centuries, rather than decades, and therefore clouding the distinct boundary of the Vernacular Threshold. An important early development in construction practice, which can be identified in the evidence of twelfth and thirteenth century peasant dwellings, was the introduction of stone walls, sills or padstones in favour of earth-fast posts, together with the adoption of crucks (Chapter 4; 4.5, for discussion in relation to the Scottish context). These innovations would have served to protect organic or earthen elements from rising ground-water, rain-water splash and flooding, simultaneously providing the permanence of great timber investments. Given this, it may be argued that the choice of a recyclable, vernacular walling material was irrelevant to notions of permanence or impermanence as it was modifications to superstructures that determined longevity. Excavations at the deserted settlement of West Whelpington, in Northumberland, have shown fifteenth century clay-mortared vernacular dwellings to have been occupied for centuries and Wrathmell suggests that agricultural developments and changes to housing trends in the seventeenth century, rather than any structural failures, precipitated their replacement. Wrathmell stops short of insisting that typical medieval vernacular dwellings built with stone sills or padstones were truly permanent, coming to the conclusion that they may have represented a semi-permanent link between previous earth-fast timber structures and succeeding post-medieval buildings. It is argued that the key distinction between semi-permanent medieval structures and their permanent, post-medieval counterparts relates to maintenance; the former being defined by low cost of erection but with the need for regular maintenance, with this being reversed in the latter case. The idea of semi-permanence has been seen as a somewhat uneasy compromise by Longcroft (2006), who queries whether a building can be anything other than permanent or impermanent. Nonetheless, by the thirteenth century well-maintained vernacular structures were capable of surviving indefinitely as a result of their improved defences against decay.

This is of particular note in relation to suggestions that vernacular buildings of medieval date or typology have failed to survive as a result of a lack of adaptability in design rather than for structural reasons, as the material fabric of such buildings may therefore be seen as guilty-by-association in terms of perceived inferiority.

3.2.1 Inter-regional overviews of earth building in England by Harrison and Dyer

Harrison (1984, 155) made the often overlooked point that 'just as there are good and inferior building stones, so there is good and less good 'mud' and that quality of material had a regional significance so far unexplored.' Pearson (1992) has noted the correlation between the survival of mudwall structures and the quality of soils available for construction, although this would seem to undermine the importance of cultural and economic (under-)valuations as to the loss or replacement of earthen structures. Landscape survey work using GIS has suggested a relationship between the survival of the oldest extant cob buildings in Devon, pre-dating 1600, and specific geological and soil contexts (Ford, *et al.*, 1997; Ford *et al.*, 2005). Either way, Harrison's focus on materiality is a welcome and somewhat isolated contribution to explaining the history of England's mudwall building traditions, as is his emphasis on inter-regional comparison rather than intra-regional survey. In relation to divergences in the quality of peasant mudwall construction across England, Harrison points out that many buildings were likely to have been left without render and that this meant the structural qualities of the raw materials were even more central to explanations of their overall durability. This point relates as much to the speed of mixing the raw materials and raising of the walls as to the finished product. It must also be recognised, however, that protection from the weather was also provided by overhanging eaves. The siting of a building and the direction in which it faced were also factors that could be used to mitigate for driven rain or wind. There are good quality seventeenth century cob farmhouses in Devon, for example, that are rendered only on the front, perhaps for show as much as protection, whilst the rears are sheltered by rising land

(Cox, 1996). Harrison also emphasises that quality of workmanship was paramount to the architectural possibilities and time efficiencies that could be achieved during the building process. Typically, for example, each lift in a mud wall is required to dry out somewhat before the next can be added. In Devon, however, Harrison explains that the quality of the raw earth and skill of mud masons allowed cob to be continuously built without hiatus between the placing of lifts, with the result being a highly compacted and slightly bulging base. Williams-Ellis' (1921) interest in earth building included the wet method as well as rammed earth techniques, and he was likewise eager to stress that the presence of poor quality cob dwellings was more likely the product of inadequate building technique rather than the structural deficiencies of the materials. Williams-Ellis provides accounts of the cob mixing process and of the particle size analysis of 'a sample of typical old cob walling', finding the following proportions of material:

	Per cent.
Stones (residue on a 7 by 7 [2.83 mm by 2.83 mm] Mesh sieve)	24.40
Sand, coarse (Residue on a 50 by 50 [297 µm by 297 µm] Mesh sieve)	19.70
Fine sand (through 50 by 50 Mesh sieve)	32.50
Clay	20.60
Straw	1.25
Water, etc.	1.55

(Williams-Ellis, 1921, 36)

When surveying mudwall buildings it is possible to identify the height of each lift and Harrison reckons that these could vary between as little as 6" (15.2 cm) and over 2' 6" (76.2 cm). This relates to the maximum amount of material that could be added without slumping and was determined by the quality of the raw earth, the addition (or not) of aggregates, the amount of water added and overall skill of the workmen involved. Above all else, however, Harrison explains the divergent mudwall building traditions of England through the geological circumstances of the localities from which he draws example. The suitability of the raw earth of an area was key to the height of lifts and overall height of walls, their load-bearing capacity and durability over time. All other factors were secondary to this, although the quality of workmanship was clearly limiting regardless of the quality of subsoil.

A hugely valuable assessment of medieval earth building in England, with particular emphasis on mud walls, has been provided more recently by Dyer (2008). Using financial accounts, Dyer has confronted presumptions about the quality of earth buildings in late-medieval England, demonstrating the use of mud across wide geographical and social spectra, in a variety of structures and at variable expense. He points out that the mundane records from which he has explored earth building are, by definition, absent of opinion and that writings by the educated and wealthy classes of later periods, such as in the Enlightenment Era, are from where negative perceptions of earth buildings as backward and poverty-stricken emanate. Dyer's work emphasises that mass earth building materials were used as much out of choice as necessity and warns against the pitfalls of accepting interpretations that have been inherited from the pretensions of eighteenth century elites who associated traditional materials with primitive populations. The assertion that building with earth was often a positive choice is an important qualification. It seems an obvious, yet often overlooked, point that

'it would be difficult to argue that stone, timber and wattles were always in short supply in those places where earth walls were preferred. It could not be suggested that those places where earth was used as a building material were especially poor, nor that their inhabitants were living at a primitive level' (Dyer, 2008, 65).

Dyer emphasises the ubiquity with which earth was used for building across parts of rural and urban England and the variety with which earth was employed as a multipurpose construction material, highlighting accounts of clay being acquired to make the floors of ground and first-floor rooms, as a waterproofing material in ponds and leats. He also acknowledges that clay was used alongside turf as a roofing material, as has been similarly highlighted in Scotland by Fenton (1970). Dyer notes that the term 'mudwall' is most commonly used when explicit reference is made in the records to buildings of mass earth, and it is suggested that the use of terms such as earth, red earth, white earth, loam, clay, loam, marl or mud were used as specific delineations depending on the characteristics or intended use of the material.

In assessing the cost of building earth walls across England between the thirteenth and fifteenth centuries, Dyer demonstrates a wide spectrum of building projects and the variability with which expenditure was outlaid, thus undermining assumptions about the use of materials based on social status, although the scope of his study is still far from geographically comprehensive. Records attest to earth buildings being erected at the behest of lords, such as in the case of a byre at Holcombe Rogus in Devon; also, to the erection of an earth wall in the great garden of Lambeth Palace and its subsequent maintenance by successive archbishops of Canterbury, who themselves were at the upper echelons of 'a society sharply attuned to outward symbols of status'. Clearly there was some degree of social significance attached to choices of building materials in relation to the types of structures built, with earth acceptable for ancillary projects but not necessarily suitable for deliberately expensive and labour-demanding aristocratic houses. Nevertheless, Dyer points to still-standing examples of cob buildings in Devon as evidence that yeomen's houses or even church houses would be built in massed earth equally as in the case of the poorest habitations.

The costs of constructing earth walls between the thirteenth and fifteenth centuries were closely related to the labour market, with a spike occurring as a result of population loss and consequential labour shortages from the later fourteenth century, before by the later-fifteenth century prices fell again in some instances to below earlier-fourteenth century levels. The evidence shows the cost of fifteenth century mudwalls to vary in accordance with the social range of those who built them. The cost per perch (variably defined as between c. 5 m and c. 7.6 m [Parliamentary Papers, 1820]), this being the equivalent of the length of a single bay, could range from as little as 9d. up to as much as 4s. 10d., with around 2s. a typical amount. Mudwall buildings inhabited by skilled artisans or high-ranking peasants, who undoubtedly had certain levels of expectation for their living environments, could be comparable in their cost to those of equivalent size erected with timber-frames and wattle and daub panels, structures such as which may have held a more romanticised place in the national memory than their massed earth counterparts. Building mass earth walls was not an artisanal occupation, but was sometimes carried out by labourers who earned only around 1d. per day in 1300 and 4d. by the fifteenth century, or by the owners of a building with the assistance of family or community members. The range of processes involved in the erection of earth walls were often recorded, including digging the subsoil and carrying it by cart or basket if the chosen pit was not contiguous to the building site and the provision of stones for protective foundation walls. The additional costs of straw, which was greater than that for earth and labour in the case of Merton College, Oxford, in 1289-90, are also attested to. Furthermore, the provision and carrying of water, essential in giving the raw earth a suitable consistency for building, could far outweigh the cost of construction, as for the byre walls erected at Holcombe Rogus in 1371-2 (Dyer, 2008).

3.3 Intra-regional evidence across England, Wales and Ireland

The following headings and contents, which deal with Wales and Ireland in their entirety but divides England into regions, reflect the quantity of literature available for each of them and does not mean to imply that further localised circumstances were not in place. The absence of evidence pertaining to Yorkshire and Northumberland, for example, reflects the paucity with which the subject of earth building has been acknowledged in these areas, rather than an absolute absence of earthen materials and traditions.

3.3.1 England

3.3.1.1 South West

According to Pearson and Nother (2000, 32), there remained probably over 5000 earth-walled buildings in Dorset when assessment was made at the turn of the twenty-first century. Keefe's conservative estimate suggested at least 20,000 standing cob houses in Devon with similar numbers of ancillary structures in the early twenty-first century (Keefe, 2005, 26). McCann (2004) attests to the extensive concentration of cob across the south west and indicates that some of those buildings found in Devon date to the fourteenth century. Indeed, the endurance of the earth-building tradition of south-west England stands apart from the rest of the United Kingdom and Ireland, despite the continued loss of a great number of historic examples into recent decades (Keefe, 2005; Ford *et al.*, 2005). The region has provided an ideal study area for large landscape assessments of cob building, with Ford *et al.* (1997) highlighting the close proximity of water sources to such surviving structures, which are often found facing south or south-east on sloping locations up to as much as 150 m above sea level (Ford *et al.*, 2005).

Fig. 3.2. Bridford Barton, Bridford, Devon. Cob and stone built farmhouse of early to mid-fourteenth century origin. (Photo credit: © Mrs Jean M. King C.P.A.G.B.).

Fourteenth and fifteenth century documents have revealed how cheaply cob buildings could be raised over long periods, with accounts known for the building of 10½ perches of mudwalls, enough to build two two-bay structures, for a tenement in Bradpole, Dorset, in 1457-8 (Dyer, 2008, 67). Including the costs of materials' transportation, stone foundations and labour, provided by the tenant himself at rates comparable with those recorded elsewhere, each perch was erected for around 9d. This compares favourably with costs known from Suffolk and Southampton some 130 years earlier of between 5d. and 9½d. per perch. Dyer explains this cost-effectiveness as a symptom of the vernacular tradition, whereby the localised nature of resource acquisition, self-building and possibilities for labour to be acquired from within the community of tenants in exchange for goods or services in kind. This example fulfils the stereotypical version of medieval earth building by the lower social order but has been shown to not necessarily be the rule. Although the cost of a complete two-bay building at Bradpole may have been as little as 20s., a comparable structure at Bishop's Clyst cost upwards of £6 in 1406 and in the urban setting of Exeter a two-bay malthouse was contracted in 1478 at £8 (including the cost of a gutter). Harrison (1999) documented the conservation and repair in the 1990s of Bowhill, an Exeter mansion house with extensive areas of cob walling dating to c.1500 (Fig. 3.3). The existence of such a building emphasises the point that proprietors of any social standing could choose to build using earth, without making the link between material and status. It is interesting to note, however, that higher social status was no guarantee of the suitability of a building site's underlying soils to construction. Analysis of an original internal segment of cob at Bowhill revealed a material composition of 3.5% clay, 28.5% silt, 41% sand or gravel and 27% gravel or stone. This would be typically deemed a weak cob mix, with a lack of adequate binding fraction and therefore leaving it susceptible to water ingress and erosion. Nonetheless, the building has stood for around 500 years and, with appropriate management, should continue to stand for the foreseeable future.

Fig. 3.3. The mansion house at Bowhill, Exeter. (Photo credit: © Mr Rex L. Haythornthwaite).

By the early nineteenth century, when the influence of Improvement was encroaching on the cob tradition and giving cause for reports to be made to the Board of Agriculture, cob work was given as costing 3s. 6d. per perch in North Devon. This still compared very favourably to the inclusive costs of building in stone, however, which was somewhere in the region of 5s. to 6s. per perch (Cox, 1996, 22). Throughout the United Kingdom it seems that negative appraisals of earth building traditions have emanated from the opinions of outsiders and it has been noted by Cox (1996) that in the Georgian period local historians tended to view cob as a source of pride, whilst improvers who arrived from elsewhere made links between backwardness of population, industry or agriculture and the buildings they encountered.

3.3.1.2 East Anglia

East Anglia has an idiosyncratic earth building history, with, contrary to most of Great Britain and Ireland, the introduction of a new typology of earth buildings from the late-eighteenth century, explained by Bouwens (2000) as a practical solution to increased population and associated demands on building materials. The novel earth-built structures that proliferated in the region during the nineteenth century were erected using ‘clay lump’, essentially unfired moulded bricks of similar material composition to cob. Clay lump building was popular in the years of the brick tax, between c. 1790 and 1860 according to Tipping (2010), although there are suggestions that the technique could have had medieval-period precedents in the area. Interestingly, eighteenth century buildings in the Devon villages of Thouverton and Bradninch have been identified as being partly built in large mud bricks. It has been suggested that this could have represented an attempt to establish a local alternative to fired bricks in an area that was geographically peripheral until the arrival of the railway, which then provided alternative building materials from outside the region (Cox, 1996). Mass earth building was also prevalent from at least the medieval period in East Anglia, with traditions comparable to those found elsewhere and the use of clay as an infill between timber uprights or in the building of plinth walls upon which timber superstructures were raised.

Archaeological evidence in this region has offered greater insights into the nature and extent of such structures than many other areas, with both rural and urban environments revealing the importance of mudwalls to the historic building stock even where surviving evidence above ground is absent. Longcroft (2006) has consolidated a range of excavation data to demonstrate this point, emphasising geological context as an important initial qualification. Dominated by glacial drifts, the few types of building stone that are found locally were reserved for higher status building and woodland was also relatively sparse from at least the time of the Domesday Book recordings. Such environmental circumstances would have had a great impact on vernacular building practices, with budgetary constraints and the abundant availability of earthen materials encouraging widespread mudwall construction from at least the eleventh century through to the early sixteenth. Excavations of Alms Lane in Norwich, conducted in the 1970s, revealed that massed earth walls were commonplace in this medieval urban environment, with some 90% of pre-1500 walls on the street built in clay. Across the medieval city of Norwich such earthen buildings were eventually replaced by equivalents of flint and brick rubble, although the point at which this occurred varied from street to street. Westwick Street, for example, replaced its earthen buildings in the thirteenth and fourteenth centuries but those of Alms Lane were retained until the early sixteenth. Although this apparently natural course of replacement conforms to expectations, Longcroft has emphasised that presumptions of earthen building techniques as being inferior and associated only with the lower end of the social spectrum are mistaken. The Abbot of Creake Abbey is known, for example, to have built a townhouse using clay in the 1330s before later letting it out to wealthy merchants. Clearly it was possible to build houses in earth that were deemed of sufficient quality to meet the standards of living expected by the medieval equivalents of town-dwelling middle classes.

Vernacular earth building was widespread in rural Norfolk. Longcroft (2006) has noted that deserted village settlements such as Thuxton and Grenstein have proved an important source of evidence, and has also highlighted that clay parsonages were built in the east of the region into the late-eighteenth century. He uses this latter observation as a means of attesting to the unbroken nature of Norfolk’s earth building traditions. This is slightly misleading, however, when read in the context of a more recent discussion provided by the same author. A shuttered clay barn identified at North Farm in Great Hockham, Norfolk, in 2009, which probably dates to the second half of the eighteenth century, has been suggested as being a ‘missing link’ between the medieval mudwall and nineteenth century clay lump earth building traditions of the region (Longcroft, 2009). In line with the theory of the Great Rebuilding, Norfolk's medieval earth buildings were largely superseded in the early-sixteenth century by materials such as flint and brick and few earth-walled structures of 1550-1800 have been identified in the region. The existence of the North Farm barn indicates, however, that vernacular earth building traditions did not completely die out at the advent of the sixteenth century. Given Longcroft’s previous references to proof that the earth building traditions of East Anglia were unbroken, therefore implying widespread continuation, it may be more accurate to think in terms of them having been retained but in a state of relative dormancy as a result of the cessation in building earth dwelling houses in the medieval tradition. Longcroft (2006) has also postulated that the practice of building dwellings in earth was mostly annulled in post-medieval Norfolk as a result of emerging trends for two-storey living, to which mudwalls are relatively unsuitable, and increased concern in urban environments for protection against fire. Perhaps such factors played a key role in the replacement of massed earth buildings nationally.

Unlike the earth building traditions of elsewhere in Britain and Ireland, examples of East Anglian clay lump are more widespread. McCann (1987) has suggested that clay lump dwellings emerged in Cambridgeshire and eastern Scotland at the end of the eighteenth century. Credit for the first adoption of the technique is afforded to a bricklayer named Joseph Austin, who constructed a cottage using ‘bats’ 8 km south of Cambridge in 1791. McCann also cites the entry for Errol in Sinclair’s *Statistical Account of Scotland* as evidence that unfired clay bricks were being used in Perthshire as a novel remedy to local building issues. McCann’s research into the emergence of clay lump building in Norfolk and Suffolk has gained wide acceptance. The prior consensus supported by various writers over the course of the twentieth century was that clay lump was first employed in the seventeenth century or earlier. This notion is quashed by McCann (1997), however, with the suggestion that building with clay lump evolved from a practice of constructing dovecotes using small unfired bricks called clay bats, referred to in documents from the late-sixteenth century. This explanation forms the basis of the later article, although his earlier work outlines the primary reasons for the adoption of the technique in the nineteenth century. These include increased interest in improving the living conditions of cottagers and increased pressures to rapidly build new structures as a corollary to agricultural improvement and labour influx; new incentives to save on building costs induced by rising timber prices and the advent of a brick tax in 1784; and, the emergence and circulation of technical and influential literature on earth building, particularly from abroad. McCann does not infer a hierarchy of importance to his list of factors, although it would seem clear that some would have had far greater significance than others. His discussion of the technical literature that emerged from later-eighteenth century France, for example, does not offer convincing evidence of a direct influence on the trend to build in clay lump, with the economic and social explanations more convincing.

Fig. 3.4. Hilltop House, Botesdale, Suffolk. A prime example of early nineteenth century clay lump construction. (Photo credit: © Prof John N. Buxton).

Although McCann successfully undermined evidence used by his predecessors in their assertions that clay lump was a more ancient technique, Longcroft has more recently urged caution in accepting outright that clay lumps were a unique innovation of the late-eighteenth century. He cites the potentially revealing but currently unknown evidence of unexcavated medieval clay buildings and findings of unfired clay blocks in an eleventh century timber church in Norwich Castle, as well as chimney stacks built using unfired clay bricks in late-sixteenth century houses in south Norfolk (Longcroft, 2006). Perhaps the most significant aspect of the widespread adoption of clay lump building in nineteenth century East Anglia are the implications for how earth-built structures could be perceived positively against the national context of replacement that occurred with increasing zeal following the medieval period. McCann highlights the glowing terms used by those seeking to improve the housing stock when describing clay lump cottages, with a particular emphasis on the neatness and regularity that the finished article produced.

3.3.1.3 The Midlands

Hurd (2000) has discussed the variability of soil types in the East Midlands, noting how this led to inconsistency in performance characteristics. He speculates that the most suitable material to be found in this region is chalky boulder clay, which is notably resilient to shrinkage. Hurd also alludes to the use of straw as a means of improving the binding strength of silty clays found in Lincolnshire and supposes that the poorer quality of these soils for building accounts for the additional use of ‘stud’ frames. Furthermore, it is suggested that the use of clay subsoils was maintained in the building of ancillary structures and the homes of the poor, in spite of the availability of stone, for economic reasons. An important caveat to this is provided, however, with the recognition that older surviving buildings display an earlier use of earth in higher status farms, buildings and perhaps manors. Evidence from fifteenth century

Northamptonshire corroborates this point, with investment made by the lord of the manor at Morcott for the rebuilding of a tenant's three-bay earth-walled dwelling in 1430-1 at up to 2s. 9d. for each of the eight perches built. Furthermore, poles for spars were imported from the manor of another lord at significant cost and thatching and tiles came to 24s. 6d. and 9s. 6d., respectively (Dyer, 2008, 68). Evidence from the West Midlands indicates that medieval lords sought to secure the maintenance of their tenant buildings' stock, with court records of the 1370s revealing fines for tenants who allowed their buildings to fall into decay and demands for adequate repairs or rebuilding to be carried out where necessary (Dyer, 2008). As shown through evidence relating to Lambeth Palace, mudwalls could be built for ancillary structures in the properties of those in the highest echelons of English medieval society. This point is also borne out in evidence from the South Midlands. Excavations in 1972 at Wallingford Castle, Oxfordshire, revealed well-preserved, load-bearing mass earth walls in a three-roomed kitchen building within the castle complex. This building measured 8.5 m by 12.5 m internally, with the walls surviving to a height of 1.8 m. Sections of lime plaster were also recorded on two of the walls. The castle itself was of national significance, being raised by William I shortly after the conquest in 1066 on top of the north-east corner of a pre-existing Saxon *burh*, and remained of royal and national importance for over 400 years. The archaeological evidence has demonstrated that the mudwall kitchen building was in use for an extended period between c.1150 and 1225, its floor having been sunken by 10 cm as a result of cleaning and the walls themselves exhibiting signs of repair and maintenance, before back-filling (Carr, 1973). The state of preservation of this medieval earth structure is worth noting as it would seem that the decision to replace it was not one based on deterioration, thus highlighting the potential longevity of mudwall buildings even before the introduction of stone plinths.

Finn (2009) has suggested that local variations in mass earth walling have been under-represented in appraisals of earth building traditions. He points to the mud and frame tradition of Leicestershire, which is defined by upper levels of daubed timber framework set into a lower-level of mass earth typically reaching to between 1.4 m and 1.7 m atop a low stone plinth. This plinth is not associated with the timber superstructure, which rests on padstones, and is thus purely associated with the protection of the mudwalls. It has been suggested that mud and frame buildings can be dated to the later-seventeenth and earlier-eighteenth centuries and could therefore be seen as a bridging point whereby older vernacular methods were developed to meet post-medieval expectations of two-storey living. Finn's investigation of mud and frame is based primarily upon assessment of around a dozen surviving examples. Some of the buildings identified exhibited a typical issue in the identification of historic mudwalls whereby replacement or concealment using brick makes them somewhat invisible on superficial assessment. It is suggested that mud and frame can be seen as a product of geographical, geological and cultural factors particular to southern Leicestershire, with the distribution of surviving examples falling within an upland area of heavy clay where woodland was scarce from at least 1200. Mudwall building was naturally common in the area prior to the emergence of mud and frame construction, whilst surrounding regions contained greater proportions of stone and timber reserves. Mud and frame combined previously distinct mudwall and timber frame building practices and although they are found in a relatively confined area, such environmental circumstances were not unique across a wider context and it remains eminently possible that the technique could have been considerably more widespread.

3.3.1.4 Cumbria

The blurred distinction between populations at the border between northern England and southern Scotland has meant that shared cultures and traditions have spanned the divide for centuries. One manifestation of this was in building practices, where vernacular motivation was ruled by aspects of resource availability and suitability that were indifferent to national boundaries and this was most apparent in the clay dabbins of the Solway Plain. Similarly to a point made by Walker in relation to Scotland, Harrison (1989) emphasises the illusion of longevity engendered by the dry stone or lime mortared structures of the rural north and reiterates the ubiquity with which earthen materials were employed in the majority of buildings that preceded those designed by professionals. This region exhibits a set of very particular geological and social circumstances that Brunskill noted were intrinsically related to local building practices. The geology of the Solway Plain determines that it was devoid of building stone and rich in clays. In addition, proximity with the Scottish border had a profound impact on society in the northernmost counties of England. Harrison has built on this association through a more considered appraisal of Cumbrian soils and geology, emphasising the inherent suitability of the Solway Plain's local boulder clays to mudwall building and, conversely, the incongruity of using rounded stones for building.

A number of authors have noted that Cumbria's clay dabbins are often characterised by shallow lifts, sometimes as little as 5 cm deep and interlaid with straw, and most explain this as a product of life in border-reiving territory where speed of construction was paramount and there was insufficient time to allow deeper lifts to dry before adding another (Messenger, 1994). Brunskill highlights that the risks of living in medieval Cumberland prompted a stark choice to build either durable stone towers or 'cheap and easily rebuilt hovels' (Brunskill, 1962, 57). Examples of lift heights more comparable with those in the mud walls of other regions are known, however. In spite of being cheap and easily rebuilt, a recent survey attests to the survival of upstanding clay dabbins dating to the fifteenth century (Oxford Archaeology North, 2006), rather than the previous consensus of seventeenth century (Brunskill, 1962; Harrison, 1989), again undermining the temptation to disregard the potential permanence of mudwall buildings of medieval origin (Fig. 3.5). The speed of erection was also related to the communal nature of the building process, with neighbours coming together to erect a clay dabbin in only a day or two, using straw layers in between lifts to help guard the walls against slumping under their own weight. It is attested that this custom, which culminated in celebration, continued into the first quarter of the nineteenth century (Brunskill, 1962).The monetary costs of raising the walls of a clay dabbin in these circumstances were therefore negligible, though the costs in labour were great. This point has been raised by Jennings, who has attempted to calculate the man hours required to erect a mudwall farmhouse of around 15 m by 6 m, single-storeyed in the longhouse tradition. All told, Jennings estimates a total investment of 3400 man hours (Jennings, 2002). Although this is at best a rough estimation, it does serve to underline the critical importance of community collaboration to vernacular traditions. Jennings has also commented on a document which, by inference, has been identified as pertaining to the repair of a mud walled barn in 1779. Rather than shedding light on the cost of raising an original structure, which in the Solway Plain was unlikely to have included expenses for mud or labour due to the communal nature of vernacular construction, the document gives insight into the transitional process of improvements to traditional building that became increasingly typical towards the late-eighteenth century. Mud would be the only walling material available without any associated costs for winning or transporting and thus is identified through its absence. At a total cost of £42 12s., it is clear that the structure was deemed of sufficient quality to warrant extensive modification in line with Improvement motivations without need being felt to replace the traditionally raised mud walls with equivalents of imported stone (Jennings, 2008).

Fig. 3.5. Brewery Farm, Cumbria. Originally listed by English Heritage at late-seventeenth century, this clay walled structure has been recently dated by Oxford Archaeology North to the late-fifteenth century using dendrochronology. (Photo credit: © Mr John Wright).

Brunskill used the records of eighteenth and nineteenth century travellers and observers to trace the extent to which clay dabbins once abounded on the Solway Plain, simultaneously noting the perceptions of these commentators in relation to local mudwall dwellings. Mirroring trends in contemporary Scottish sources, many of the later-eighteenth and nineteenth century opinions encountered are imbued with the rhetoric of Improvement. Suggestions that mudwall buildings were outmoded, impoverished and in need of replacement were typical, although hints of sympathy were also identified. Furthermore, emphasis is given to the crucial differences in perception between those outside onlookers and the local inhabitants of the dabbins themselves. Nonetheless, the association between Cumbrian mud walls and the poverty of at least some of their inhabitants is given credence by the suggestion that mudwall dwellings were raised without stone plinths – as noted earlier, a development of the medieval period – as late as the early nineteenth century (Harrison, 1991). It is even suggested that the decline of clay building correlates with a simultaneous decline in communal festivities, this being explained by Brunskill (1962) as a result of the greater value and reduced suitability in layout of replacement brick or stone homes.

3.3.2 Wales

There is a paucity of research into specifically Welsh earth building traditions, yet the region undoubtedly has a noteworthy history of utilising earthen materials in construction and extant mudwall cottages were recorded in the 1970s in the less mountainous west (Penoyre and Penoyre, 1978). The deeper history of earth building in Wales is testified, for example, in the place name Pontypridd, which translates as bridge (*pont*) by the earthen house (*ty pridd*) (Nash, 2000). Nash (1994) summarised that earth was an inferior building material in Wales, being employed only when stone and timber were unavailable or too expensive, although this must be qualified by the point that vernacular building materials are not necessarily hierarchically defined in accordance with their physical properties. Stone cottages are known from the country around Snowdonia in Wales, for example, where the freely available loose stone was utilised to build simple dwellings by local populations (Alfrey, 2002). Wiliam (1998) has provided a more in-depth study of vernacular earth building in Wales, reiterating the connection between such materials and the lowly status of those who employed them. This account emphasises the importance of studying Welsh vernacular buildings as a means of accessing a material record of the lives of the past rural majority, with the focus on eighteenth and nineteenth century landless cottagers. The enclosure of common land from the later-eighteenth century resulted in cottagers claiming parcels, effectively as squatters, by building 'one-night' dwellings. These were a temporary means of claiming land and were literally constructed overnight, often using turf. It has been argued, however, that memories of these makeshift structures hold greater significance as an abstract reiteration of common land rights than as vestiges of a lost vernacular (Alfrey, 2002).

There does seem, however, to be a lack of appreciation for any of the more middling peasant population and one wonders as to whether further research into the medieval roots of vernacular building may reveal that structures with earthen components were erected in

Wales by a greater cross-section of the population, as has been demonstrated in relation to various regions of England. Wiliam's explanation of Welsh vernacular building conforms to typical accounts that take the lack of surviving examples as evidence of impermanence. He states that 'Because of the nature of these buildings – they used poor quality materials and did not last long – we know little about them until the middle of the eighteenth century, although their virtual absence shows that they were not good enough to last more than a century or two, in contrast to farmhouses which survive fairly commonly from the seventeenth century in Wales' (Wiliam, 1998). Wiliam does identify two areas, south Cardiganshire and north Carmarthenshire, where mudwall structures survive and describes them as being 'built in courses some two feet high upon a stone foundation' (Wiliam, 1998, 14). Furthermore, the *Department of Scientific and Industrial Research Building Research Board* (1922) attested that cob cottages were erected in South Pembroke as late as the 1880s. Alfrey (2002) has collated various nineteenth century sources testifying to walls of mud in buildings found across Wales, including a suggestion of shuttering being employed. Furthermore, 'significant numbers' of surviving examples are known in Ceredigion and the Llyn peninsular, although these are perhaps exceptions to the rule of nineteenth century replacement. If one were allowed license to speculate that such dwellings were the successors of earlier medieval equivalents then this would begin to suggest the possibility of reasonable quality mass earth buildings existing in Wales, with the potential that the reasons for their lack of survival into the present are more nuanced than the explanation of material inferiority.

3.3.3 Ireland

Oram (2000) has explained that evidence of earth building in Ireland prior to 1500 can be found through archaeological record, with scant surviving evidence above ground. Gailey (1984) has shown that later mudwall houses survive into the present, perhaps aided by encouragements to improve, rather than replace, such dwellings in some nineteenth century literature. Concentrations of earth buildings are particularly prevalent in County Armagh, with the qualification that many mass earth walls are hidden by render and 'a veneer of modernity'. This is an important point, particularly in relation to Scotland, as the earth-built heritage is easily cloaked and therefore overlooked when viewed superficially. Nevertheless, the gradual erosion of the earth building tradition resulted in very few earth houses being built beyond the nineteenth century with the consequential loss of knowledge and first-hand witnesses of methods of erection (Oram, 2000). Surveys more recently have suggested that 49% of traditional rural buildings identifiable on Ordnance Survey maps of 1909 have been lost, with a further 39% significantly transformed (Devlin, 2003). It may be suggested that perceptions of earth building in Ireland are particularly tainted by links with nineteenth century poverty and oppression and this may have contributed to particularly neglectful twentieth century management policies. The photography of Hugh MacConville in the late-twentieth century attests unequivocally, however, to the existence of various fine examples of mudwall construction across the south east portion of the Irish landmass (MacConville, 1997).

Gailey (1984) provided a valuable contribution to the study of vernacular building in the north of Ireland, tracing the history of earth building in the area through archaeological evidence of Bronze Age building with sods to still-standing mudwall structures. It is emphasised that even sods or peat, which have for centuries been synonymous with buildings of poverty, could be used in more than a temporary fashion. Well-designed houses with whitewashed peat walls recorded in the 1940s testify to this assertion. McDonald and Doyle (1997) identified the remains of mudwall building traditions across much of Ireland, with the exception of the west and south-west coasts. Like Gailey, they date the origins of mudwall building in Ireland to the Anglo-Norman period. Prior to this it is likely that the majority of early medieval dwellings consisted of drystone or post-and-wattle walls, with earthen elements being used in the form of clay floors and turf roofs (O'Sullivan and Nicholl, 2010). It should be noted, however, that not all parts of Ireland necessarily experienced the introduction of mudwall building simultaneously. Robinson (1979) has attributed the introduction of mass earth construction in Ulster to the arrival of English and Scottish settlers in the early seventeenth century, with the region being previously typified by nomadic roundhouse structures, known as creats, which were built with timber, wattles and sods. He does however acknowledge evidence that could suggest the presence of mudwalls prior to the seventeenth century, such as Barthelet's map in 1600. O'Conor (2002) has also discussed the situation in Ulster, citing a combination of cartographic and archaeological evidence attesting to sub-rectangular dwellings in later medieval Ulster with earthen walls (whether mud, sod or wattle and daub), which were most probably associated with crucks. Although a lack of excavation across the remainder of the Irish landmass leaves questions as to the extent to which such buildings proliferated, there is good evidence to suggest that they were in use much further south in fifteenth-to-seventeenth century Munster. Furthermore, the close association between crucks and mud walls, the performance of both having been shown to be intrinsically related to the advent of plinth walls and padstones, serves to undermine Robinson's account as these building elements may well have arrived in Ireland with Anglo-Normans in the thirteenth century.

The apparent lack of a western distribution of mudwall is explained by McDonald and Doyle (1997) to be related to the prevailing wet and windy weather from Donegal to Kerry. These authors have shown an intriguing range of views towards mass earth building in Ireland. They identified sympathetic reviews of mudwall building practices in the *Irish Farmer's Journal* in the early-nineteenth century, with buildings in County Wexford being deemed neat, clean and commodious. The skill with which such dwellings were erected also received praise, whilst social and economic circumstance was not deemed a limiting factor on the nature of inhabitants. A more typical nineteenth century appraisal was found in the 1878 edition of *The Irish Builder*, in which the persistence of such buildings in Irish landscapes was bemoaned with typical references to barbarity and the moral duty of landowners to ensure their replacement.

Reminiscent of Clough Williams-Ellis' advocacy of the reintroduction of earth building in England, McDonald and Doyle reveal a suggestion made by Frank Gibney in 1942 to the Industrial Research Council. In this, he proposed that the widespread availability of suitable subsoils and superiority of mudwalls to their modern, thinner equivalents made building in mass earth eminently logical, with the only barrier being negative perceptions which by the mid-twentieth century had come to predominate.

3.4 Conclusion

Theories such as that of the Great Rebuilding, the name of which alone implies a necessary, momentous, cathartic renewal, have influenced perceptions of traditional building materials and techniques dating back to the medieval period. Historians have gradually revised the revolutionary nature of changes in methods and styles of building, with evidence that robust peasant structures can be traced to the thirteenth century and formed the basis of more gradual developments in the history of the quality of English building. Dating evidence testifying to the longevity of mass earth building practices has generally proved scanty in the literature, with the analyses of surviving examples having been relied upon by practitioners from the 1960s to 1980s. Increasingly, documentary and archaeological investigations are being used to add dating and economic details regarding the invisible and, historically speaking, most valuable body of evidence relating to the lost majority of vernacular earth buildings that once littered the British and Irish islands.

The acceptance of earth as a building material across the social spectrum over a long period of time should be noted as an important qualification for inherited perceptions. The importance of underlying geological and environmental factors in explaining the nature of local traditions and disparities in the quality of buildings from place to place must also be carried forward as important contextualising information. The notion that vernacular buildings of medieval origin were inherently impermanent is an assumption that has often been made without a full appreciation of materials and methods of construction. It would seem churlish to suggest, for example, that loadbearing mud walls over 0.5 m thick could have ever been interpreted as insubstantial or reliant on a minimal investment of labour or finance, or both. The insights provided here, which benefit from geographically and academically wide-ranging appraisals, are of great value to historical interpretations of earth building in Scotland. These would otherwise be limited by a relative lack of competing scholarly interest. These insights must be carried forward into the following discussion on Scotland's earth buildings, thus helping to inform the inferences made.

4. Hidden heritage: the past ubiquity, environment, and perceptions of lost earth buildings in Scotland from the medieval period to the era of Improvement

This chapter considers a range of evidence, based on the synthesis of previous field survey work, archaeological records, inferences from work consulted in the previous chapter, and a variety of documentary source material. The latter of these is particularly valuable in examining perceptions, analysing social contexts and providing a sense of the lost intangible aspects of Scotland's earth-built heritage. This last point is suitably encapsulated in the following account.

4.1 Late-eighteenth century mudwall construction in Dornock, Parish of Dumfries

In the first place they dig out the foundations of the house, and lay a row or two of stones, then they procure, from a pit contiguous, as much clay or brick-earth as is sufficient to form the walls: and having provided a quantity of straw, or other litter to mix with the clay, upon a day appointed, the whole neighbourhood, male and female, to the number of 20 or 30, assemble, each with a dungfork, a spade, or some such instrument. Some fall to the working the clay or mud, by mixing it with straw; others carry the materials; and 4 or 6 of the most experienced hands, build and take care of the walls. In this manner the walls of the house are finished in a few hours; after which, they retire to a good dinner and plenty of drink which is provided for them, where they have music and a dance, with which, and other marks of festivity, they conclude the evening, this is called a daubing; and, in this manner they make a frolic of what would otherwise be a very dirty and disagreeable job.

(Sinclair, 1791-99, **2**, 22-23).

4.2 Introduction to the history of Scotland's earth-built heritage

Earthen materials have been used in a variety of guises and in conjunction with numerous other materials for millennia as an integral part of Scotland's built environment, particularly, though not exclusively, in vernacular architectures. Even when not used as the primary structural element clay-rich subsoils have been employed to reduce friction between massive stone slabs in prehistoric tombs, applied to wall heads as a form of waterproofing, or used as mortar in stone-built structures from farmhouses to castles (Walker *et al*., 1996). This chapter investigates the history of vernacular earth-built structures in Scotland, focusing on mudwall examples, and how perceptions of such vernacular buildings were shaped and developed through periods of intense cultural and environmental change, giving consideration to the human exploitation of traditional resources. Historic earth-built structures are today deeply hidden within the landscapes of Scotland, although they were once a common feature of both urban and rural settlements. The eighteenth and nineteenth century period of Improvement – during which many of these structures were destroyed, repurposed or left to decay – has received extensive attention by historians, but there exists no serious study of the human and environmental dimensions in respect of the material aspects of landscape resource use and perceptions of such use. It is therefore sought here to emphasise the national significance of this undervalued aspect of Scotland's built and cultural heritage, increasingly at risk of being lost completely, by highlighting a prior ubiquity of mudwall structures.

Fig. 4.1. Mudwall dwelling in fine condition, photographed at Fettercairn, Kincardineshire, in 1966. (© SCRAN).

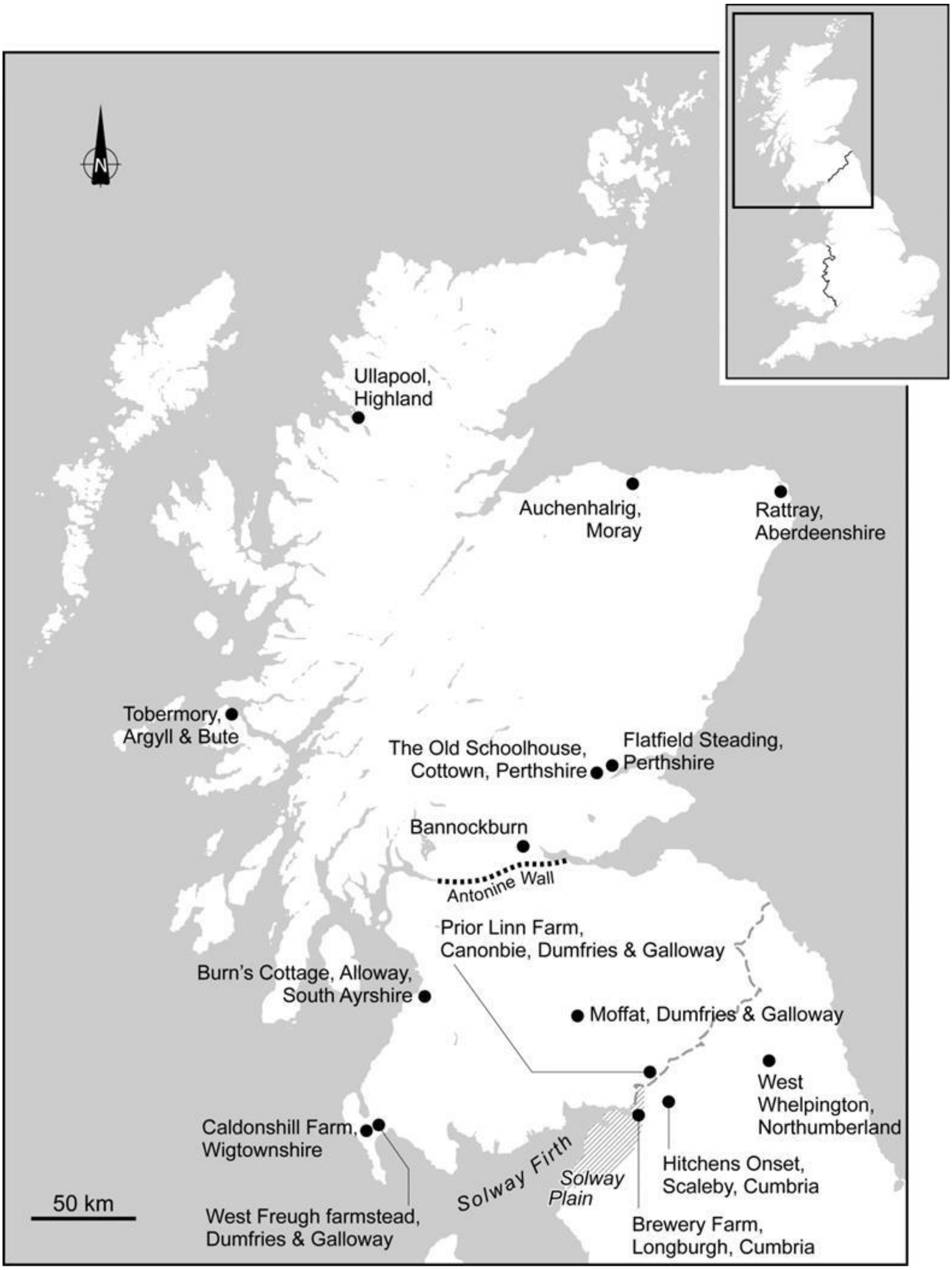


Fig. 4.2. Map of Scotland showing the locations of some of the sites referred to in the text.

Historical context is intrinsic to defining the cultural significance of the built heritage and Walker (1979, 58) commented almost four decades ago on the need for further research into 'documentary sources, especially estate records, early photographic collections, and contemporary illustrations and paintings'. A comprehensive search through Scotland's archives for information relating to earth building in Scotland has yet to be completed and it has been demonstrated for England that this can prove a rewarding and informative activity (Dyer, 2008) that bypasses issues raised by an over-reliance on surveying patterns of surviving examples. Indeed, it is safe to assume that there remains a mine of relevant information still to be discovered that could shed light onto the ubiquity of earth structures in Scotland, their geographical and social distributions, costs of building and further intricacies of construction. Some previously collated accounts can be found to include references relating to earth building materials, constructions and even disputes. Douglas' appraisal of a collection of sources relating to the burgh of Forres, for example, includes a 1586 quarrel amongst neighbours with regards to ownership of the mud lying between them, with the insinuation that the conflict was caused by the reliance of the common people on the resource for building and maintenance of their dwellings and ancillary structures (Douglas, 1934, 450). The pressure placed on the mud resource for building is also highlighted by an account from two years following, with a decree enforcing all burgh residents to build their 'heid yards sufficiently with mud or feill' (Douglas, 1934, 450) (*feill*, or fale, is a usually rectangular or parallelogram-shaped cut of turf [Walker, McGregor and Stark, 2006]), whilst clay walls are attested as diving areas in the vicinity of the tolbooth in Perth in the late-sixteenth century (NAS RH6/2681). Such examples serve to demonstrate that earth-built structures were prevalent in urban, as well as rural, environments. Documentary evidence can be used to emphasise the central place that earthen materials deserve in Scotland's heritage agenda, a point awarded further credence by the relative lack of extant structures, which, if rendered or brick-faced, are often invisible to superficial assessment. Highlighting this point, recent surveys in the Carse of Gowrie have identified upwards of 105 previously unrecorded earth buildings, forty of which are extant. Of these extant structures only four have been designated as significant enough for listing (Morton and Winship, 2012). This highlights the lack of perceived importance of such buildings, which is exacerbated by the issue of invisibility.

Although there are continuities in aspects of earth building technique and form across Britain and further afield, the great variation in Scotland's geology and surface soil make-up is reflected in the variety of ways earth, alongside other vernacular materials, has been employed as a constructional component, with notable subtleties within smaller localities being apparent (McGregor, 2010). Turf (and, to a lesser extent, peat) also provides a hugely important component in this building tradition (Whyte and Whyte, 1991; Walker *et al*., 2006), particularly in the Highlands and Islands, which is worthy of recognition here due to its relevance in the development of perceptions towards earthen structures. McKean (2006) has emphasised the distinct boundary between the Highlands and Lowlands in terms of quality of housing, although his delineation based on a division between the Tay and Dumbarton discounts large areas known as having good quality mudwall traditions stretching up the east coast through Angus (Fig. 4.3) and Kincardineshire (Fig. 4.1) to Moray and beyond. Thomas Pennant provided a notably positive appraisal of common mudwall dwellings in mid-eighteenth century Aberdeen, for example:

'The houses in this country are built with clay, tempered in the same manner as the Israelites made their bricks in the land of Egypt: after dressing the clay, and working it up with water, the labourers place on it a large stratum of straw, which is trampled into it and made small by horses: then more is added, till it arrives at a proper consistency, when it is used as a plaster, and makes the houses very warm.' (Pennant, 1776, 146-7).

Fig. 4.3. Restored schoolhouse, Logie, Angus. Built in the first part of the nineteenth century, the building was acquired by the National Trust for Scotland (NTS) in 1995 following its abandonment in 1990 and gained an A listing status. The application of cement render in the 1970s had accelerated the deterioration of the mudwalls and the building required major stabilisation and reconstruction. The Schoolhouse was taken on by the NTS Little House Improvement Scheme in 2005, with renovation works commencing in 2007 and culminating in 2008 (Romankiewicz, 2005; Copp, 2009). In 2009 the building was awarded the Europa Nostra Prize, the European Union Prize for Cultural Heritage.

The President of the Royal Institute of British Architects from 1950-1952, Graham Henderson, provided the introduction for Sinclair's *The Thatched Houses of the Old Highlands*, emphasising the ingenuity with which limited building materials had to be used despite reinforcing the notion of the noble savages of the Highlands 'poor in worldly things but rich in their love of family and their native mountains and glens' (Sinclair, 1953, 5). Furthermore, the adaptability of vernacular building methods in light of environmental context is highlighted, for example, through consideration of the temporary peat houses excavated from the Kincardine Moss during its reclamation at the behest of Lord Kames in the 1790s. Captured in sketches by the English artist Joseph Farington, these shelters were a pragmatic means of housing the poor labourers (Megaw, 1962) described by the artist himself as 'scooped out of the solid moss' (Rackwitz, 2007, 390). The blackhouses synonymous with the Western Isles, which, with their walls of turf or a double skin of dry stone filled with loose earth, were suitably developed in response to a harsh North Atlantic environment (and therefore not imported with the Norse longhouse tradition [Walker, McGregor and Stark, 2006]), perhaps formed the latter part of a tradition that encompasses the Iron Age brochs of the same region (Geddes, 2010). The suitability of such vernacular construction traditions as a response to specific environmental conditions is emphasised by the inadequacy of the replacement dwellings imposed on the St Kildan islanders from the 1860s (Carruthers and Frew, 2003).

Fig. 4.4. Left: ruined blackhouse at Geàrrannan Bay, Isle of Lewis, where such structures were built from the late-seventeenth century. Right: exposed earthen core of ruined blackhouse walls outside the village of Geàrrannan.

4.3 Turf and its importance to discussions of earth building in Scotland

Scotland's turf building tradition is relatively unique and, in the vernacular context, perhaps the most undervalued aspect of earth building more generally. Whether employed as a mass walling material or in combination with alternating stone layers (Fenton, 1968), as roofing or applied to wattle-work (Walker *et al*., 2006), turf was an omnipresent and, over long time frames, renewable resource. Loveday (2006) has convincingly argued that the missing structural elements of impressive Neolithic hall-buildings at Claish, Balbridie and Balfarg were originally occupied with since-lost turf. Loveday draws heavily upon historical and ethnographic evidence and highlights the common prehistoric use of earth and turf as wall-core infill, which Sinclair (1953) referred to as an ancient forerunner to modern cavity-wall insulation (Fig. 4.4). Over-exploitation of the turf resource carried environmental implications, however, with archaeological evidence revealing that turf-stripping for building and fuel purposes contributed to the accelerated erosion of landscapes in the Western Isles as long ago as the Neolithic (Mills *et al*., 2004). Documentary sources attest that by the late-seventeenth century the Culbin estate in Moray was ruined as a result of the over-exploitation of the turf resource for building and composting, with exposed sand at the coastal location inundating the interior (Ross, 1993). The most prominent extant turf-built structure remaining from antiquity in Scotland is the monumental Antonine Wall, comprising of laid turf walls and parallel deep ditches. Despite this second century Roman structure being abandoned within a few decades of its completion its remains still form a vast monument and have recently been subject to detailed environmental management as part of its World Heritage Site status (Historic Scotland, 2007).

Fig. 4.5. Cross-section through turf wall at the Highland Folk Museum, Newtonmore. (Photo credit: George MacLeod/Dorothy McLaughlin, 2012).

By the late-eighteenth century turf structures were seen as the lowest form of available shelter, with the influential Improver Sir John Sinclair of Ulbster calling for their construction to be prohibited. His reasons were threefold, noting the loss of potential agricultural land (a late-twentieth century turf house reconstruction at the Highland Folk Museum, Newtonmore [Fig. 4.5], used an acre of turf [Noble, 1984]); the impermanence of the material; and, the damp and 'unwholesome' living conditions that such homes created (Sinclair, 1795). The pro-Improvement agenda encapsulated by Sinclair undoubtedly impacted upon the wider vernacular built environment and can be seen as intrinsic to the process of loss and replacement within the sphere of earth building traditions. Clearly, the sort of labour-intensive activities involved in vernacular building projects, which were invariably carried out during the best part of the year, reduced the potential for greater increases in agricultural output and thus directly impinged upon the aspirations of the Improvers. The consequent attempts to replace vernacular building practices therefore provided a means by which to further free up the rural labour force and the lands on which it dwelt for economically productive endeavours, whilst simultaneously expanding the market for architecturally-designed housing and imported materials.

Common in eighteenth century travelers' diaries are references to turf dwellings as hovels, for instance in those of Edmund Burt when describing parts of Inverness (Burt, 1998) and Thomas Pennant in relation to rural Sutherland (Pennant, 1776). Such comments perhaps influenced perceptions of vernacular earth buildings more generally, suggesting low quality, impermanent structures. It is perhaps worth noting that turf and peat were not completely abandoned as building materials, however, with the latter recognised as having great utility in excavated ice houses, for example, such as those detailed by Herbert in the late-nineteenth century (Walker, McGregor and Stark, 2006). This clearly reflects the excellent thermal properties of earth building materials and the continued utility that could be found for them until relatively recently.

4.4 Building with clay-rich subsoils

The bulk of this assessment will concentrate on mass earth construction, particularly the mudwall tradition that saw a suitable mineral subsoil, typically mixed with fibrous matter such as straw, hair or heather, gravel (though not always) and water, built in layers (or lifts) on top of a low rubble or stone base until a monolithic wall of requisite height resulted. It is invariably assumed that clay was sourced from a pit adjacent to the building site, although recent landscape surveys in the Carse of Gowrie suggest that people would choose to transport clay over 500 metres or more to build on sites where it was not immediately abundant (Morton and Winship, 2012). This adds to the suggestions made in relation to England in the preceding chapters that mudwall building techniques were often positively chosen, rather than imposed due to an absence of alternative materials. Straw would on occasion be laid between lifts (Fig. 4.6) with dung, blood, urine, or other organic additives potentially used to modify the cohesion and workability of the mass building material. Surviving evidence of mass earth construction can be found across Scottish landscapes arcing from the north east to the south west. The vagaries of Scotland's geology and soils, economy and culture had great effect on local building traditions and there is no definitive ratio of materials used in the mixtures or construction technique that can be applied to all contexts (Stell, 1993). Auchenhalrig Work, also known as 'Clay and Bool' or 'Straw and Dash', a tradition distinct to the locality around a village in Morayshire in North West Scotland from which the name derives, is a variant of the claywall tradition (Fig. 4.18) that used mass earth in combination with prominent rounded boulders common in the area (Walker, 1992).

Fig. 4.6. Barn at Prior Linn, Canonbie, Dumfries and Galloway, with layers of straw laid between mudwall lifts. It should be noted that this practice could result in the increased exposure of straw to moisture and therefore decay, thus undermining the strength of the walls (Morton, 2008). (Photo taken by Werner Kissling in 1954 and held by the School of Scottish Studies Archive, University of Edinburgh).

Explanations of the drastic decline in use of earth building materials over a period covering three centuries from the mid-1700s have typically been seen as part of the narrative of the Improvement, with the imposition of an architecturally-designed building stock from pattern books being a corollary to landscape change and agricultural development (Walker, 1979). In this narrative agricultural revolution was followed by industrial advancement, the emergence of a more all-encompassing economy and the increasing availability of cheaper imported building materials following the advent of extensive railway networks. This meant that local context, climatic conditions and the lifestyles of the rural population were no longer the underlying explanations for building methods (Carruthers and Frew, 2003), whilst rural depopulation and urban expansion meant the abandonment of many small settlement areas outside of the main conurbations. Scotland's rural built landscape as it is now seen is a product of these developments and the usually stone-built structures that it holds are often viewed romantically as antiquated remnants of a previous agriculturally-reliant economy. The reality, however, is that the many stone farmhouses, with their homogenised appearances across the regions of Scotland, are generally part of a relatively modern aesthetic and an approach to construction that severed links to traditional buildings and the methods of their erection (Richards and Richards, 1994; Fenton, 2008).

The instincts of contemporary popular consciousness and many present-day heritage organisations can reinforce this narrative. In the United Kingdom the popular focus often remains on evocative buildings such as castles, country houses and early industrial premises built in stone and brick, typically overlooking vernacular structures. It is at the vernacular end of the building spectrum, however, that the experiences of the vast majority of Scotland's past rural population are best represented. To develop this understanding, distinctions must be made between vernacular buildings, vernacular construction methods and vernacular materials. This means that stone, which was deemed a necessary means of improving the building stock by the later-eighteenth century, was often found as a vernacular material. Fenton has emphasised that Orkney probably retains a greater proportion of ancient farm buildings than elsewhere in Scotland due to the flagstone beds of Old Red Sandstone that provided durable structures distinct from those often built contemporaneously with perishable earth walls across the mainland (Fenton, 1997). Martin Martin, who documented his experiences of visiting the isolated island community on St Kilda in 1697, commented that

'The inhabitants live together in a small Village, carrying all the Signs of an extreme form of Poverty; the Houses are of a low Form... The Walls of the Houses are rudely built of Stone, the short Couples joining at the ends of the roof, upon whose Sides small Ribs of Wood are laid, and these covered with Straw' (Martin, 1753, 10-11).

It is apparent that in the eyes of Martin their remote situation determined poverty and backwardness and the employment of drystone walling 'without any Wood, Lime, Earth, or Mortar to cement it' was inherent to this. Martin thought the addition of earth to stone to be a potential means of improving the quality of a dwelling, providing an apposite contrast to eighteenth century notions that the replacement of earth with stone was a route to a better standard of living for the tenant class. Thomas Morer published a description of dwellings in lowland Scotland in 1689. Writing just a few years earlier than Martin, but in a contrasting geographical context, Morer explains that

'The vulgar houses… are low and feeble. Their walls are made of a few stones jumbled together without mortar to cement 'em... They cover these houses with turff of an inch thick, and in the shape of larger tiles, which they fasten with wooden pins, and renew as often as there is occasion; and that is frequently done' (Brown, 1891, 275).

The study of the history of Scotland's vernacular building traditions has been the reserve of a limited, but therefore invaluable, body of scholars, most notably Bruce Walker and Alexander Fenton, with an emphasis on the surveying and recording of surviving examples (Fenton and Walker, 1981; Walker, 2006). *The Rural Architecture of Scotland* provided a compendium of information relating to the vast array of different types of wall and roof construction historically employed by Scotland's vernacular builders, compiled primarily from the conservators' perspective (Fenton and Walker, 1981). The efforts of Walker and Fenton in recording the variety of vernacular building methods and styles found across Scotland have proved vital to the exercise of cataloguing an ever-decreasing body of structures. Nevertheless, unrecognised and unlisted historic mudwall structures still abound, even where the technique is most renowned (Morton and Winship, 2012; McLaughlin, forthcoming; Adderley, Parkin and McLaughlin, forthcoming), and gaps remain to be filled with regard to assessing the record of earth building in Scotland from the historians' perspective, something that cannot rely on field survey alone. The paucity of competing scholarly thought validates the approach taken in this thesis, with evidence having been sought from areas of Britain where cultural continuity with Scotland is reflected in comparable building traditions. Building on the work of Fenton, Walker and others, further insight will now be given to the environment in which earth buildings, particularly of mudwall construction, were found in rural Scotland, also giving an account of how perceptions of the materials, and the structures they were employed in, developed over time.

4.5 Earth-buildings: life cycles, materials and construction

Fenton associated pre-Improvement building practices with pure functionality and outlined a key point: that local earthen materials were taken from the environment and utilised before deteriorating and returning from whence they came, making them an inherent part of the systems of traditional life in Scotland (Fenton, 2008). This natural process has also resulted in the relative lack of extant structures, with Whyte and Whyte (1991) suggesting that more is known about Iron Age rural dwellings than those of the sixteenth century. Somewhat poignantly, the discovery of sheets published in the Cromarty News from 1891 and 1892 has provided descriptions of a three-roomed mud-built 'hut' inhabited by two brothers at Navity, Black Isle, until their deaths in the 1840s when 'the 'auld clay biggin' was thrown down' for 'the ploughshare…[to pass] over where it stood' (Alston, 1994, 29). Aside from human intervention, the rapid climate changes reported for the late twentieth and early-twenty-first centuries are undoubtedly an influence on the types and rates of processes involved in the deterioration of earthen buildings. Taking a longer view we can consider the compiled set of monthly temperature records for central England as offering the most comprehensive data set for northern European temperatures of the seventeenth century onwards (Parker *et al*., 1992). Data can be examined at decadal time-steps for 1671 to 1698, where cross-referred data from the Netherlands are used, and from 1707 onwards where a wide spread of instruments are noted. This suggests, for the period prior to later-nineteenth century industrialisation, that the extremes of temperature seen in monthly data within each decade exceed any decade to decade shift (Fig. 4.7). Thus, the cycle outlined by Fenton could be considered independent of the effects of long-term temperature change. The notion that building with earth is part of a material cycle and can withstand future climate change is one that pervades in thinking that has brought about its recent revival, although successive generations of Scotland's inhabitants recognised this as part of their agricultural regimes from prehistory through to the nineteenth century.

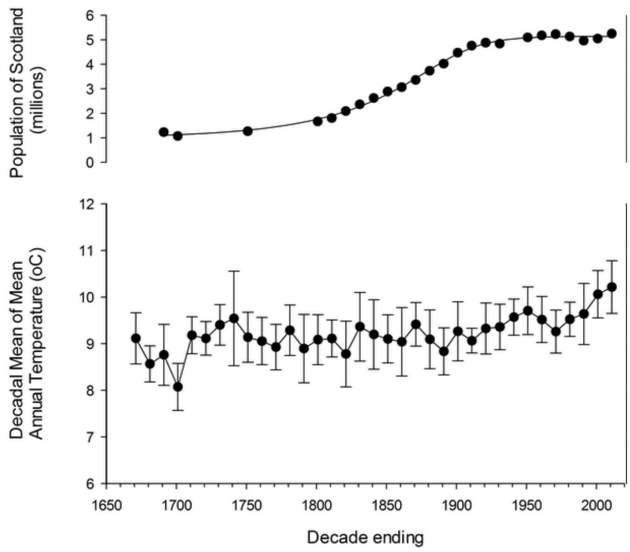


Fig. 4.7. Population and temperature statistics for Scotland from the mid-seventeenth century onwards.

Use of the words "clay" and "mud" occurs in documents relating to Scotland's earth building traditions but it is not always clear what the distinction between these terms may infer. Amongst modern commentators, McGregor (2010) has emphasised the importance of place when associating mudwall with Dumfriesshire and north-west England around the Solway Plain. Maxwell (1996) chooses to regard the material of mass earth walled structures of the north-east, the Carse of Gowrie and the Solway area as clay, without reference to mud. Also, in modern field surveys where a mass earth wall is found faced with another material, such as brick, it is generally known as 'claywall', although specific examples include clay and bool and cladded mudwall (Walker, 1992; Walker *et al*., 1996). Claywall is also used more specifically to define walls of irregular stones bound using earthen material mixed in the same way as for use in mudwall building and with the outward appearance of a masonry structure (Walker *et al.*, 1996). As already noted, when examining the Scottish landscape for mass earth buildings it becomes apparent that a greater number of examples may still exist than those that have been recorded, since buildings may be faced in a second, sometimes later, skin of more ‘permanent’ material such as stone or brick. The *Royal Commission on the Ancient and Historic Monuments of Scotland* (*RCAHMS*) has surveyed indicative examples, such as at Caldonshill Farm in Dumfries and Galloway where a brick-faced mudwall steading still stands (Fig. 4.8). Another example in Leetown, Perthshire (Chapter 7; 7.3.1.3) has experienced accelerated deterioration of its exposed mass earth walls in recent years. ‘Mudwall’ specifically refers to unfaced examples of mass earth raised using the wet method and, although claywall survives more commonly (Walker *et al*., 1996), is here deemed more likely to be typical of an original form of mass earth building. Shuttered earth construction was most likely introduced to Scotland from the continent in the eighteenth century, when interest in pisé was reignited, and claywall is used to describe what is essentially permanently shuttered mudwall. It has been suggested that Auchenhalrig Work was adopted around the same time as pisé or shuttered claywall techniques from earlier Mediterranean traditions, with the sharing of knowledge perhaps being facilitated by fish trade links (Walker and McGregor, 1999). Through the assessment of archival sources it seems that the use of the words clay and mud as raw materials was transposable, meaning that the sources may equally refer to clay mortar and mud mortar, clay walls and mud walls. This is borne out in a contract of wadset (effectively a mortgage agreement) from 1703, for example, whereby an agreement between John Sinclair and James Sinclair secured for the former ‘the free liberty and privilege of ground, stone and clay for building a girnel house’ (National Archives of Scotland (NAS) GD139/110). The compound ‘claywall’ is not prevalent in archival material, however, whereas 'mudwall' is, and it is this distinction which further corroborates the notion that 'claywall' is a more recent introduction.

Fig. 4.8. Brick-faced mudwall barn at Caldonshill Farm, Dumfries and Galloway. (© Crown Copyright: RCAHMS. Licensor www.rcahms.gov.uk).

Beyond the raw materials there is a great deal of terminological intricacy when dealing with matters of construction. Walker has proposed that the precision with which a variety of terms were once used at the local level reflects a previous diversity of building practice that has since been lost (Walker, 1977) and that the lack of a professional industry allowed various independent strains of earth building to develop (Walker, 1979). The same author has also reflected on the breadth of traditional terms once used through a consideration of the Scottish dictionaries, making the point that vernacular earth building activities held a far greater variety of descriptors than masonry work. The main body of the article from which this observation relates sought to investigate timber use, however, leaving aside any consideration of entries relating to earth building (Walker, 2005). The *Dictionary of the Scots Language* (DSL) is comprised of the *Dictionary of the Older Scottish Tongue* (DOST) and the *Scottish National Dictionary* (SND), which span the twelfth to seventeenth centuries and eighteenth to twentieth centuries, respectively. References to earth building in the DOST include: 'Clay... To smear or plaster with clay'; 'Cat... A wisp of straw combined with soft clay used in building or repairing walls'; 'Mud... (built) of mud or clay'; and 'Mude-, Mudwall... A wall built of mud or clay; the material forming such a wall'. The SND entries for some of the same words listed above provide further information, including that there once were 'professional' mud masons operating in Scotland. For example, '*clay-an'-dubber*, a builder of houses with mud walls; one who does *cat-an'-clay* work... *clay-thack*, thatch held in position by clay'; '*clay-cat*, *-kat*, a bunch of straw mixed with clay used in the building of a mud wall' (www.dsl.ac.uk). This latter technique was used to repair chimneys in the smithy at Edinburgh Castle in the early-seventeenth century (Paton, 1957, 360). Whilst being referred to in the DOST as a building material, a similar entry for 'mud' does not appear in the SND. This does not mean that the terminological use of mud in reference to building suddenly disappeared on the eve of 1700, but perhaps reflects the advent of changes to traditional building practices in Scotland.

Although there can be little doubt as to the ubiquity of earth-built structures in Scotland prior to the eighteenth and nineteenth centuries, proving this earlier prevalence through survey, archival or archaeological record poses difficulties. With extant lay buildings pre-dating the mid-eighteenth century virtually unknown, a common assumption is that poor construction and the nature of materials used resulted in buildings with short lives (Whyte and Whyte, 1991). Consideration of the arguments discussed in relation to the history of vernacular building in England leads one to speculate as to the impact that building with crucks (or 'couples') may have had on the quality of peasant buildings in Scotland, this being intrinsically related to the introduction of stone foundations. Employed as a means of protecting timbers from rotting, these low walls were also ideal for mudwall construction, protecting against the capillary rise of groundwater that is otherwise deleterious to earthen building materials. Although the assumption may be to think that the walls of the majority of medieval peasant buildings were in filled with wattle and daub, there seems no great hurdle to overcome in imagining the use of mudwall at an earlier time than sources can tell us for regions in which it is known to have been common. Dyer (2008) has pointed to a group of fifteenth century two bay cottages in Bishop's Clyst, Devon, for example, that were built using cob at a price of £3 4*s*. 0*d*. each. Although geographically disparate, Devon and certain areas in Scotland, such as parts of Angus and the Carse of Gowrie, have comparable traditions in mass earth walling and it is likely that good quality cruck and cob peasant buildings were being constructed in the Midlands and south of England during the thirteenth century (Dyer, 1986; also, Harrison, 1991). Although care must be taken when projecting evidence from England northwards, some of the evidence provides food for thought and Stell's early attempts at cataloguing the distribution of Scottish cruck building suggested widespread use of the technique across the Scottish landmass, albeit from a limited sample size (Stell, 1981). Longcroft (2006) has noted the growing body of archaeological evidence for buildings with massed earth walls from the thirteenth and fourteenth centuries from southern England to Wales, Northern Ireland and Scotland, also asserting the presence of such buildings in rural and urban Norfolk from at least the eleventh century. As seen, a great deal of research into the history and nature of earth building around the Solway Plain, in north-west England, has been conducted by Brunskill, Harrison and Jennings (Brunskill, 1962; Harrison, 1989; Jennings, 2002), with recognition given to the continuity of this tradition into south-west Scotland. Dorothy Wordsworth who noted 'here and there an earth-built hut' on the Solway Plain during her journey northwards in 1803, recorded 'clay cottages every half or quarter of a mile' along the banks of the River Nith near Dumfries (Wordsworth, 1997). A survey of 312 sites with complete or partial remains of historic clay dabbins in Cumbria has resulted in the reappraisal of this building tradition. Previously dated to no earlier than the seventeenth century, there is evidence amongst the surviving 306 buildings that these small dwellings and agricultural buildings were constructed from at least as early as the fifteenth century. Examples have been identified at Brewery Farm, Longburgh and Hitchens Onset, Scaleby, and another at Ratten Row, Durdar, dates from around 1505 (Oxford Archaeology North, 2006).

Elucidating on the impact of the emergence of cruck building in England, Wrathmell's (2002) allusion to the tendency of scholars to consider medieval peasant building as impermanent and of poor quality is used to explain the lack of surviving examples prior to the introduction of 'improved' farmhouses in the sixteenth and seventeenth centuries. Taking an archaeological perspective, Wrathmell reasoned that following the abandonment of settlement sites vernacular walling materials would have inevitably perished and structural timbers reused elsewhere as a matter of economic sense. This assertion is particularly valid when consideration is afforded to the increasing dearth of good quality timber. In Scotland, the shortage of timber was causing concern to Parliament in the sixteenth and seventeenth centuries and led to a series of Acts for the protection of the resource (Smout, 2005). Ross (2012) has demonstrated the extreme pressure on timber resources for building in late-sixteenth and early-seventeenth century upland Banffshire, where turf-walled structures with timber couples would be rebuilt every seven years. The consequent burden on the managed timber resource in Strathavon alone is estimated at almost 200,000 trees per annum, although this may well have been moderated through coppicing (Ross, 2012) and re-use of the 'permanent' cruck frames. On a wider scale, such factors surely put greater emphasis on the need to erect decent quality buildings with alternative, cheap, durable materials, of which we can think of well-built mudwalls as one. Dixon (2002) has discussed the emergence of cruck building in lowland Scotland in the thirteenth to fourteenth centuries. Archaeological evidence from excavations of the deserted medieval settlement of Rattray, in Aberdeenshire, revealed fourteenth century clay- and clay and rubble-walled buildings (Murray and Murray, 1993). These structures appeared to succeed thirteenth century buildings that were primarily of wood and the authors of the excavation report postulate that this may have been directly correlated with the exhaustion of local timber supplies. Standing survivals of cruck-framed mudwall buildings can be found in Scotland, such as at Prior Linn Farm (Fig. 4.9), which can be thought of as part of the wider building tradition around the Solway Firth.

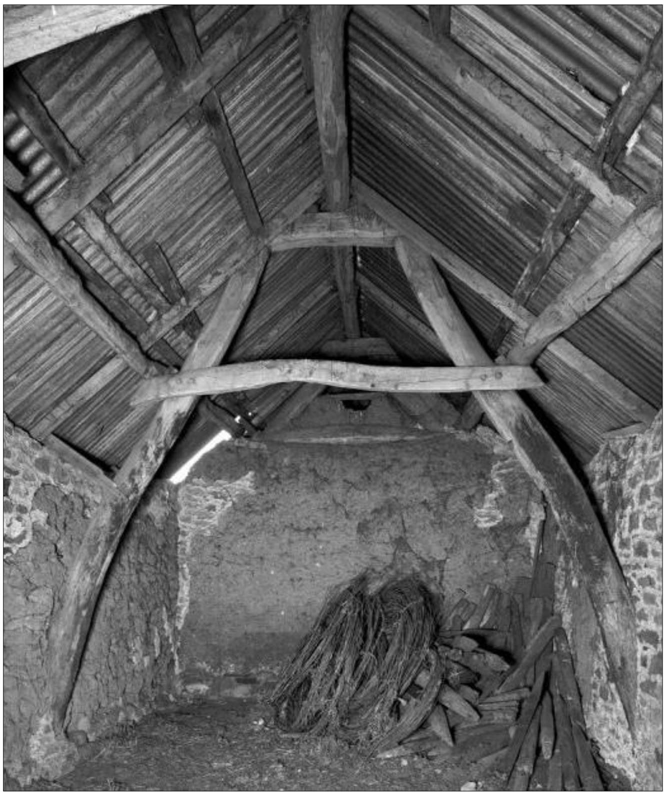


Fig. 4.9. Cruck and mudwall at Prior Linn Farm, Canonbie, Dumfries and Galloway. (Photo taken by Werner Kissling in 1954 and held by the School of Scottish Studies Archive, University of Edinburgh).

At this juncture, it is important to emphasise how historic earth-built vernacular structures could be made entirely permanent in spite of the damp Scottish climate when built with stone plinth walls and appropriately maintained with regular new thatch and lime harl. Therefore, the propagation of negative perceptions of vernacular mudwall dwellings must be partly explained by disparities in the quality of build and suitability of external finish. The misguided application of cement render in recent decades (such as at Flatfield Steading in the 1970s, for example; Chapter 7; 7.3.1.2) has caused damage to numerous mass earth buildings as this impermeable covering traps moisture within the walls, causing them to slump. This simultaneously highlights the loss of knowledge in how to maintain earthen materials in the craft tradition and encourages the interpretation of such walls as impermanent. Likewise, it might be assumed that many mudwall buildings of lower status were left unrendered upon completion, leaving them unprotected from water infiltration and wind erosion and therefore liable to loss. A further important qualification is that the relative ratios of cost to maintenance, rather than longevity of a building's life-cycle, can determine perceptions of permanence. Thus, the notion follows that true permanence is determined by high initial cost and low-level maintenance, while semi-permanence is defined through low building cost with a need for frequent subsequent maintenance and repair (Wrathmell, 1984). The latter qualification defines the essential nature of historic earth-built structures, although Longcroft (2006) has questioned the relevance of cost to maintenance ratios by emphasising that the upkeep of medieval vernacular dwellings required minimal amounts of both cost and skill.

4.6 Prior to Improvement – the Bannockburn Papers

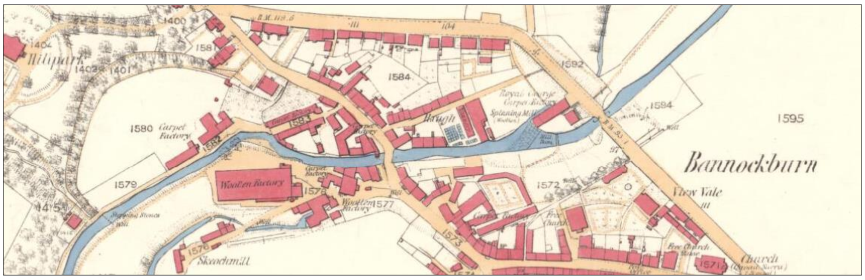


Fig. 4.10. Bannockburn as surveyed in 1857 by the Ordnance Survey – note Skeochmill, bottom left.

A novel insight into the extent to which mudwall dwellings and agricultural structures of a type envisaged in the discussion above once proliferated in Scotland is afforded by the post-1715 Forfeited Estate Papers for Bannockburn, Stirlingshire. Within the papers, the 'Accompt of the Quantitie and Qualitie of the lands tenents and hereditaments Which Belonged to Sir Hugh Patersone' (NAS E616/1), from 19th November 1716, provides details of the lands and buildings held by sixty named tenants and the rentals they paid to the forfeited landowner prior to his demise. The landscape around Bannockburn, the Carse of Stirling, is extremely low-lying and, as mentioned in relation to the Kincardine Moss, renowned for having been cleared of its extensive cover of peat over a number of decades from the 1760s. The Carse of Stirling was not composed of peat-topped bogs alone, however, as many accounts would lead one to believe (Harrison, 2003), and the patchwork of agricultural and moss lands stretching from the Upper Forth were attested to in the maps of William Roy in the mid-eighteenth century (Figs. 4.11 and 4.12) (crucially, prior to the advent of drainage and clearance). The Carse of Stirling has widespread clay soils (Fig. 4.13) (with these being buried where great depths of peat were and still are found) and Stirling gives its name to the clay soil Association found locally and that covers over 400 km^2 of Scotland's landmass (Wilson *et al.*, 1984).

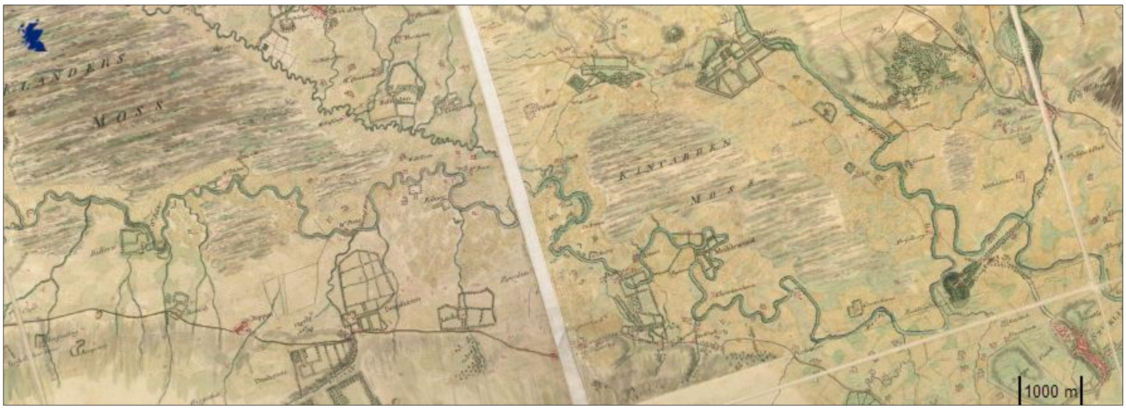


Fig. 4.11. Roy recorded the Kincardine and Flanders Mosses to the west of Stirling as discrete entities within a mixed landscape. NLS Maps

Fig. 4.12. The settlement at Bannockburn is shown by Roy in the 1750s as being within agricultural land (spanning the break in the map sheets), with a discrete area of bog lying to the east. NLS Maps

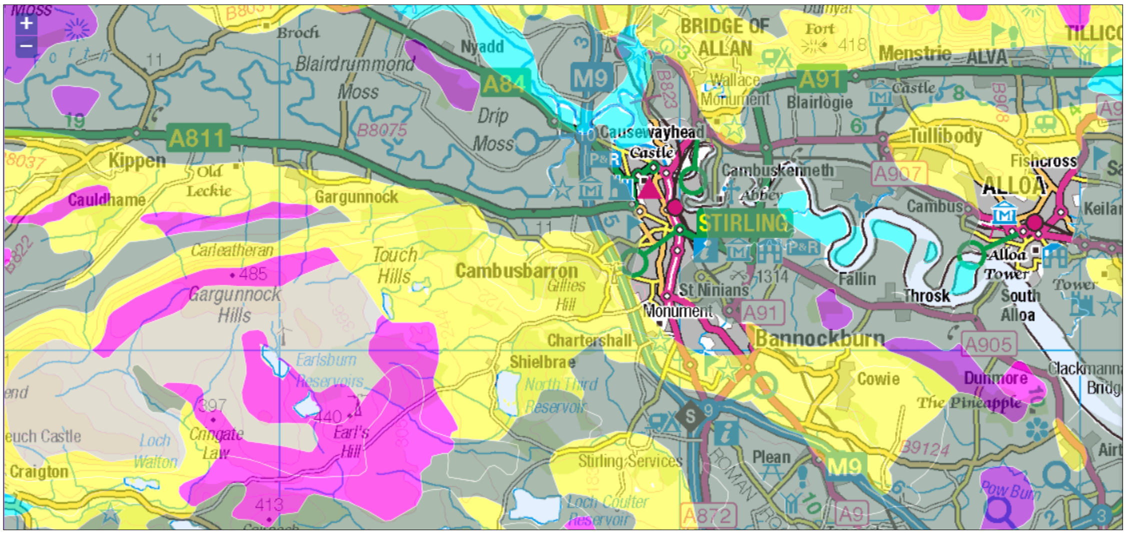


Fig. 4.13. The 1:250,000 Soil Map of Scotland indicates a mixed landscape of soil types around Bannockburn, including Stirling Association noncalcareous gleys (grey), brown earths (yellow), blanket peat (light grey), peaty gleyed podzols (pink) and mineral alluvial soils (blue).

Of the nine feuers and fifty-one possessors named in the Forfeited Estate Papers, a number held multiple dwellings, suggesting that sub-letting was prevalent, contributing to an impressive total quantity of buildings on this single estate. The list is noticeably split between those named as ‘fewars’ or had holdings ‘in few’ and those who were said to ‘posess’ certain buildings and lands. Most of the structures included in the account have a description of the wall fabric used, with twelve tenants having ‘stone and mudd’ buildings and twenty-seven having ‘mudd’ or ‘muddwall’ equivalents. Nearly all structures mentioned are said to have been ‘thatched with straw’, with the roofs of the few remaining buildings unspecified. Of the buildings without descriptions for the walling materials, twenty-six are cott houses and two are simply ‘houses’. Of the twelve tenants who held buildings of ‘stone and mudd’ one of these had only ‘Ane room’ within a house, five had a single dwelling house and the remainder had multiple ‘little houses’. Of those with multiple little houses, one feuer had nine, including one with two stories; another feuer had five and there was also one with two. Two of the possessors in the list had six bays’ worth of houses (it is important to note the pluralisation of ‘houses’) built in stone and mud and another had four bays’ worth. For medieval England, Dyer points to the dimensions of a single bay as being around 15 feet by 15 feet (c. 4.6 metres by 4.6 metres), noting that examples of buildings of such size, although limited, are known to have existed, thus supporting the notion that a minimum dwelling space size can be given as only a single bay within a multiple-bay construction (Dyer, 1986). Discussing vernacular building in pre-Improvement Banffshire, Ross has quoted information from Dixon in suggesting that cruck spacings could range between 6 feet (1.8 metres) and 19 feet (5.8 metres) (Ross, 2012). Based on the number of bays, a maximum total of thirty-eight potential dwelling spaces built with stone and mud can be identified, ranging from a single room to a two-storey house. One of these dwelling houses was specified as being 'two Couple length', thus directly suggesting a similar building template to medieval structures built with crucks. The descriptions of buildings with multiple bays may also imply the use of cruck construction if it is given that each bay equated to the space between two sets of crucks. Of those tenants with mudwall buildings, seven held a dwelling house, barn and byre, consisting of four bays in length, one of which was a 'Sitt' house. Two tenants held the same but with three bays' length, whilst one other had only two bays for his. The number of bays for two of the tenants with dwelling house, barn and byre are not given, but one of these also possessed 'Ane malt kiln and some Cott houses all built with mudd and thatched with straw, And Consisting of about fifteen bey'. Twelve of the tenants' holdings were described as having varying numbers' 'bey of mudwall houses', five of which included barn and byre, again implying a row of separate dwellings within a larger partitioned structure. Of these, eleven buildings of three to four bays' length and one of six to seven bays were listed. This theoretically equates to somewhere in the region of fifty potential mudwall dwelling spaces (working on a minimal basis of one bay for each) across the twelve building rows. This can be added to those apparently larger dwellings with multiple bays and the fifteen bays' worth of cott houses for a total of up to seventy-seven mudwall dwellings or dwelling spaces and seventeen associated outbuildings or agricultural extensions. A near-contemporaneous account of the costs involved in repairing the same type of mudwall structure as proliferated at Bannockburn can be found for Cuttlebrae, in Moray, where one George Simpson carried out repair works for Janet Falconer at the following costs:

	[Scots] £ s. -d.
Imp. for winning and leading in of mud for repairing mudd walls	00-05-00
It. for going to the hill for pulling of heather for easings to the house	00-16-08
Itt. for cutting of three thousand and three hundred diviots	01-03-04
Itt. for leading the forsaid diviots	01-13-00
Itt. for thacking two days	01-03-04
Sum of all it.	06-14-04

(NAS GD44/51/542/4)

The Bannockburn account is particularly useful for studying the deeper history of earth building in Scotland as the pre-Improvement structure of landholding was probably still retained, with some small parcels of estate land still worked for subsistence purposes rather than being consolidated into large enclosures for capital gain. Furthermore, the middling tenants could retain surplus incomes after paying their master with what was taken from sub-letters (Devine, 2006). Feuers tended to occupy mud and stone buildings on the Bannockburn estate and possessors tended to occupy mudwall buildings. If this situation is considered in conjunction with the lands worked by these people then inferences can be made about their relative social standing and how this related to the building materials used. Also included in the Bannockburn papers are declarations dated three days later than the account, by William Dollar, Lilias Cowan and James Walker, tenants who held nineteen year tacks for extensive holdings. Dollar and Cowan together held 'the miln of Skeock which is two storey high and about fourty foot long built with stone and lyme and sclaited as also two corn kilns with a ruinous maltbarn which wants the roof all built with stone and mudd and thatched with straw, And suchlike ane dwelling house ane storey high and about thirty six foot long, built with stone and lyme and thatched with straw… ane barn byre & stable with several coalhouses all consisting of twelve bay or thereby built with stone and mud and thatched with straw'.

For this, together with twelve acres of marginal land, they were committed to paying £416 13*s*. 4*d*. Scots, plus twenty bolls each of oatmeal and 'multured meal', twenty four capons and 'half of the land tax and publick burdens'. The same tenants also rented two stone and lime dwelling houses about 60 feet in length, one of which had two stories, with a further three acres of land, in exchange for a further £8 3*s*. 4*d*. Scots. James Walker's possessions included

'two milns with a loft in each of them both built with stone and lyme both about seventy foot long and thatched with straw or Beat as also ane maltbarn and kiln with a little loft therein built with stone and mudd and thatched with straw and suchlike a dwelling house consisting of seven bay of length all built with stone and mudd and thatched with straw together with barn byer and stables and severall cotthouses all consisting of about fifty bay or thereby all built with stone and mudd and thatched with straw and only ane storey high'.

For this, together with forty acres of reasonable land, Walker paid £340 Scots, twenty bolls each of bear (bear, also referred to as bere, is a hardy variety of barley [www.dsl.ac.uk]) and oatmeal, three bolls of oats, ten threaves of straw, thirty-nine each of capons and hens and half of the land tax and public burdens.

This information, together with that provided in the account, provides a level of inference in regard to a hierarchy of preferred building materials and methods on the Bannockburn estate. Naturally, investments in the mills meant that stone with lime mortar was the walling material of choice for these valuable assets Dollar and Cowan also maintained three dwellings in the same materials, two of these being fairly commodious. The fact that these tenants held longer-term rental agreements was presumably further incentive to make financial investments in their buildings. Beyond these stone and lime structures, however, all of the outbuildings mentioned, as well as James Walker's seven bay dwelling and fifty bay cotthouses, were of stone and mud. These tenants clearly held a higher status than the majority of those living on the estate and this was reflected in their maintenance of buildings with stone walls. Mud mortar, however, was deemed more than sufficient for most buildings on their higher-investment holdings and it is perhaps telling that James Walker's cotthouses, unlike most of those in the account, had walls of stone (although this, as already discussed, is no guarantee of superior quality). Nonetheless, the individuals named in the account were above their unnamed lessees in the social pyramid and the inclusion of named and unnamed cottars in the list adds to the suggestion of a graded population that partly operated on a basis of labour services being given in exchange for parcels of land worked for subsistence (Devine, 2006). This further indicates the numerous gradations that could have existed across the varying quality of buildings if social status is considered.

Table 4.1. Summary of relevant information within 'Ane Particular Accompt of the Quantitie and Qualitie of the lands tenents and hereditaments which Belonged to Sir Hugh Patersone (lately attained for high treasone) With ane Exact and particular accompt of the yearly Rents and outmost values thereof And how the samen are held. Faithfully made and Given up By the Fewars Tenents and Posessors of the samen after named In the terms of And Conform to the late act of Parliament Naming Commissioners to Enquire in the Estate of Certain Traitors' (NAS E616/1/10)

Name	Status	Houses/ other	Barns and byres	No. bays/ length	Materials	Cott houses	Bays	Materials
John Robin	Fewar	ane house two story high	No	about forty foot long	-	Nine	-	All thatched with straw
Name	Status	Houses/ other	Barns and byres	No. bays/ length	Materials	Cott houses	Bays	Materials
James Buchan	Fewar	ane laigh thatched house	No	-	stone and mudd; thatched with straw	-	-	-
Archibald Wordie	Fewar	Nine little houses...one whereof is two story high	No	-	stone and mudd; thatched with straw	-	-	-

David Brown	Fewar	ane house	No	two Couple length	stone and mudd; thatched with straw	-	-	-
John Steill	Fewar	ane room of ane thatched house	No	-	stone and mudd; thatched with straw	-	-	-
William Andersone*	Fewar	two little houses	No	-	stone and mudd; thatched with straw	-	-	-
William Keir*	Fewar	two houses	No	-	stone and mudd; thatched with straw	-	-	-
John Loackart*	Fewar	ane little house	No	-	stone and mudd; thatched with straw	-	-	-
Henry Hill*	Fewar	ane little house	No	-	stone and mudd; thatched with straw	-	-	-
William Gillespie*	Posessor	ane little house	No	-	stone and mudd; thatched with straw	-	-	-
James Burden	Tenant	ane little dwelling house	Yes	about four bey	mudd; thatched with straw	-	-	-
John Lourie*	Posessor	ane little dwelling house	Yes	about four bey	mudd; thatched with straw	-	-	-
Andrew Gray*	Posessor without tack	ane little dwelling house	Yes	about four bey	mudd; thatched with straw	-	-	-
William Smith*	Posessor by tack	ane little dwelling house	Yes	about four bey	mudd; thatched with straw	-	-	-
Thomas Smith	Posessor	houses	Yes	three bey	mudd	-	-	-
William Andersone*	Posessor	houses	Yes	three bey	mudd	-	-	-
John Wright	Posessor	houses	Yes	six or seven bey	mudd	-	-	-
John Frizall(?)	Posessor	-	-	-	-	ane	-	-
Alexander Hall	Posessor	-	-	-	-	ane	-	-
John Hall	Posessor	-	-	-	-	ane	-	-
John Andersone	Posessor	-	-	-	-	ane	-	-
Alexander Mackie	Posessor	ane house	Yes	about four bey	mudd; thatched with straw	-	-	-
Name	Status	Houses/ other	Barns and byres	No. bays/ length	Materials	Cott houses	Bays	Materials
John Steven*	Posessor	ane house	Yes	about four bey	mudd; thatched with straw	-	-	-
Stepehn Watson	Posessor	ane house	Yes	about four or five bey	mudd; thatched with straw	-	-	-
John Glen	Posessor	ane house; ane malt kiln	Yes	-	mudd; thatched with straw	some cott houses		mudd; thatched with straw

John Johnston*	Posessor	four bey of houses	Yes	-	mudd; thatched with straw	-	-	-
John Jaffray	Posessor	ane sitt house	Yes	about four bey	mudd; thatched with straw	-	-	-
John Burges	Posessor	houses	-	seven bey	muddwall; thatched with straw	-	-	-
William Dow	Posessor	ane house	Yes	about three bey	muddwall; covered with thatch	-	-	-
Alexander Jaffray*	Posessor	ane house	Yes	about three bey	muddwall; covered with thatch	-	-	-
James Atchesone	Posessor	ane little dwelling house; ane walkmiln	-	-	muddwall; thatched with straw	-	-	-
Andrew McGowan	Posessor	houses	-	four bey	muddwall; thatched	-	-	-
Gabriel Andrew	Posessor	houses	-	four bey	muddwall; thatched	-	-	-
John Andrew	Posessor	houses	-	four bey	muddwall; thatched	-	-	-
Duncan Young	Posessor	-	-	-	-	ane little cotthouse	-	muddwall; thatched with straw
John Russall	Posessor	houses	Yes	three or four bey	muddwall; thatched	-	-	-
John Gillespie	Posessor	houses	-	four bey	muddwall; thatched	-	-	-
David Robertsone	Posessor	houses	-	four bey	muddwall; thatched	-	-	-
Helen Logon	Posessor	ane house	-	-	muddwall and stone; thatched	-	-	-
Mareon McFeal	Posessor	ane house		two bey	muddwall; thatched	-	-	-
John Hall	Posessor	houses	Yes	about six bey	mud and stone; thatched	-	-	-
Isobel Russall*	Posessor	houses; ane maltkiln	Yes	about six bey	mud and stone; thatched	-	-	-
James Miller	Posessor	houses		three bey	muddwall; thatched	-	-	-
Margarat Richards	Posessor	-	-	-	-	ane cotthouse	-	-
Robert Stevensone	Posessor	-	-	-	-		-	-
Thomas Taylor	Posessor	-	-	-	-	ane cotthouse	-	-
Name	Status	Houses/ other	Barns and byres	No. bays/ length	Materials	Cott houses	Bays	Materials
John Donaldsone	Posessor	-	-	-	-	ane cotthouse	-	-
Agnes Mitchell	Posessor	-	-	-	-	ane cotthouse	-	-
Alexander Drummond	Posessor	-	-	-	-	ane cotthouse	-	-

David Andersone	Posessor	-	-	-	-	ane cotthouse	-	-
John Rae	Posessor	-	-	-	-	ane cotthouse	-	-
John Tannoch	Posessor	ane house	-	-	-	-	-	-
Graham Walker	Posessor	-	-	-	-	ane cotthouse	-	-
Alexander Johnston	Posessor	-	-	-	-	ane cotthouse	-	-
John Lourie	Posessor	-	-	-	-	ane cotthouse	-	-
Edward Hall	Posessor	-	-	-	-	ane cotthouse	-	-
John Richardsone	Posessor	-	-	-	-	ane cotthouse	-	-
Alexander Cowan	Posessor	-	-	-	-	ane cotthouse	-	-
James Murehead	Posessor	houses	-	-	stone and mudd; thatched	-	-	-
William Andersone	Posessor	-	-	-	-	-	-	-
*those marked with an asterix are described as having possessions of the quantity and quality of the previous entry								

4.7 Perceptions of Scottish vernacular buildings from the medieval period to the era of Improvement

Perceptions of Scottish vernacular buildings have undoubtedly developed and altered over time, although the attitudes of those who historically built and lived in vernacular contexts are rarely known. Most records that relate directly to earth building in Scotland come from the eighteenth and nineteenth centuries, due to the pertinence of peasant building practices to Improvement ideologies. The transitional Improvement era instigated a trend within Scotland's political and social elites to perceive earth-built structures in a negative light, with connotations of barbarity, backwardness and poor health. Nevertheless, even the *Statistical Account of Scotland* and *General Views* compiled for the Board of Agriculture, which are so fundamental to understanding Improvers' attitudes to ways of rural existence deemed outmoded by the later-eighteenth century, contain some sympathetic treatments of vernacular building practices. The period during which these were compiled also saw the popularisation of travel writing, typified by the likes of Pennant, Boswell and Johnson and the Wordsworths. Some useful references can also be found in travelers' accounts from prior centuries, though, either through inference or specific allusion.

In the late-nineteenth century Peter Hume Brown (1891), the first Sir William Fraser Professor of Scottish History at the University of Edinburgh, compiled a series of accounts made by foreign visitors to Scotland prior to the eighteenth century, including that of Thomas Morer previously mentioned. Brown's collection was based on printed sources rather than original manuscripts and it can be assumed that a number of the visitors' generalised descriptions were based on limited stays in the country or the plagiarism of other descriptions. These can, however, still be considered of value as a means of gaining early travelers' views of Scotland (Rackwitz, 2007). The earliest account in the collection is from Æneas Sylvius Piccolomini, the future Pope Pius II, who in the mid-fifteenth century painted what became a fairly typical outsiders' view of Scottish lay dwellings. His description of living conditions notes that 'the roofs of the houses in the country are made of turf, and the doors of the humbler dwellings are made of the hide of oxen' (Brown, 1891, 26-7). Although overt judgments of these vernacular building materials are avoided, use of the term 'barbaros' clearly emphasised links between Scottish society and living conditions with backwardness and a lack of civilisation (Rackwitz, 2007). The next relevant account found in Brown's collection, provided by the French visitor Jean de Beaugué in c.1548-49, relates the presence of a fort at Montrose 'built on moving sand and being constructed of dry turf' (Brown, 1891, 66-7). This suggests that there was a continued practice of building not only humble dwellings from earth-based materials but also monumental structures, even if the integrity of the construction was being questioned. Evidence for the use of earthen materials in fortification has been identified by Fenton, with sources relating to Scottish castle building demonstrating that some peel towers constructed in the borders in the later-sixteenth century were erected using clay (Fenton, 1970). William Mackay Mackenzie, the Scottish historian and archaeologist, promulgated the idea that clay-built castles may once have been prevalent in Scotland based on an interpretation of evidence taken from *Hakon Hakonsson's Saga*, originally written in c.1264-65 (MacKenzie, 1934). Mackenzie argued that the 'hewing' with axes of the 'soft stone' walls of Rothesay Castle could only be explained by the fact that the original walls were in fact clay-built and made hard 'like stone' upon drying. Although this specific claim has been repudiated in more recent times (Oram, pers. comm.), there is some evidence to suggest that early castles could have been raised using earth. *The Romance of Fergus* (or *Roman de Fergus*), for example, which was written at the behest of Alan of Galloway to celebrate his marriage to Margaret, daughter of the Earl of Huntington, in 1209, includes the following lines:

'Upon a great dark coloured rock
he had his house right nobly set
Built all about with wattle work
upon the summit was a tower
That was not made of stone and lime
of earth the wall was builded high
And crenelated, battlemented,
The farmer was full glad to own
So fair a home above the sea
For thirty leagues he had a view
Around him if he cast his gaze.
Who is within need have no fear
Of escalade or engineer…'

(Ewart *et al.*, 1985, preface)

It is unequivocal that earthen materials were used in castle and elite architectures throughout the later medieval period in Scotland (Fig. 4.14) (as elsewhere across Europe [Fig. 4.15) for a variety of purposes. Accounts from Holyroodhouse in 1529-30 indicate the use of turf and clay in essential repair works, with 4000 divots used in ‘the mending of the gilehous in the abbay for the keeping of hay to the kingis cart hors’ ‘iii dosoun [dozen] of clay to the beymfilling ande beting [repairing] of the samyn hous’ (Paton, 1957, 7). Furthermore, clay mortars are found commonly at castle sites across the country. It should be noted that stake and mud dividing walls are still to be found at Foulis Castle, amongst others.

Fig. 4.14. Stake and mud dividing wall in Foulis Castle, near Evanton, Highland. (© SCRAN).

Fig. 4.15. Beaten mud floor on the top level of Siedleçin Tower, Lower Silesia, Poland. This was laid above the ceiling of the underlying level, where it is visible through the timbers, and provided good insulation for the Great Hall below.

Estienne Perlin, the French ecclesiast and physician, provided a brief, bleak account of vernacular building in Scotland in c. 1551-2 that describes the houses of the common people as 'badly built and proportioned' (Brown, 1891, 74). Perlin had a vested interest in emphasising Scottish national poverty so as to aggrandise the position of its French ally and there is a lack of evidence to suggest Perlin ever actually set foot in Scotland, adding to the idea that hearsay and stereotype contributed as much as personal experience in forging perceptions of a country on the northern fringe of mainland Europe (Rackwitz, 2007). Thomas Kirke added to earlier accounts in the later-seventeenth century by specifying some of the materials typically employed in common dwellings. *A Modern Account of Scotland by an English Gentleman*, published in 1679, is unsympathetic in describing the living conditions of the bulk of Scotland's population:

'The houses of the commonalty are very mean, mud-wall and thatch the best; but the poorer sort live in such miserable huts as never eye beheld; men, women and children pig altogether in a poor mouse-hole of mud, heath and some such like matter; in some parts, where turf is plentiful, they build little cabins thereof, with arched roofs of turf, without a stick of timber in it; when their houses are dry enough to burn, it serves as fuel, and they remove to another' (Brown, 1891, 260).

Kirke asserts the ubiquity of mudwall and turf building in Scotland by relating them to the houses of the masses and, although he inevitably regards all of their dwellings as 'very mean', his opinion that mudwall homes were superior to the other types of earth-built structures witnessed seems creditable. Records of seventeenth century mudwall buildings of higher status such as the manse of King Edward parish in Aberdeenshire (Beaton, 1997) serve as testament to the quality of earthen buildings Kirke may have come across on his visit to Scotland. Kirke's descriptions are full with diatribe and prejudice, concealing the reality of his experiences. The published *Account* of 1679 was preceded by a three-month tour in 1677, however, during which he kept a diary that was straightforward and free of the negative embellishment found in the published work. As Rackwitz (2007) has explained, the diary reflects well on Scotland generally, being both appreciative and praising, suggesting that the version presented in his *Account* was deliberately created for the benefit of an audience familiar with anti-Scottish diatribes.

Attempts to replace the nation's peasant building stock from the mid-eighteenth century provided a watershed in the gradual loss of most of Scotland's earth buildings. Efforts to deal with the Jacobite rebellions could be seen as one of the catalysts for, and inherently part of, the popularisation of later eighteenth century Improvement ideology in Scotland. Comprehensive accounts drawn up by government officials, such as that for Bannockburn, detailed the rental agreements between tenants and forfeited landowners and allowed for an assessment of the population and economy of Scotland, leading to suggested improvements to education, agriculture, industry and infrastructure. 'Papers relating to Improvements' were compiled between 1761 and 1784 and these can be aligned with the *Statistical Account* and *General Views* in relation to the changes to building practice that they encouraged. Amongst these post-1745 papers are those relating to 'Leases' and within them can be found a section entitled 'Encouragement for building better houses'. This prescribed in 1761 that 'stone, lime and great timbers' should be used in the erection of houses by 'masons, wrights and thatchers', with tenants obliged to undertake repairs 'with the like materials' (NAS E730/32). The requests of tenants for allowances to assist with the erection and repair of 'good stone and mudd walls' within a decade of these prescriptions reflects a continued perception that the improvement of dwellings could be achieved without lime (NAS GD44/24/3/3). Although others sought to maximize opportunities for financial assistance in replacing mud with lime in the late-eighteenth century (NAS GD112/11/2/3/85), caution should nonetheless be practiced when assuming that new stone buildings were necessarily lime mortared, even into the nineteenth century, as mortar traditionally referred to the use of mud to provide the bond between walling stones and misinterpretation of this in more recent times has falsely led to assumptions that documents referring to stone and mortar equated to the use of lime (Hutcheson, 1927). Furthermore, the building stipulations proposed by government were not even necessarily adhered to by those complicit in the imposition of post-forfeiture protocols, with the erection of 'mud or clay' houses near Beauly being contracted by one commanding officer in order to house the burgeoning numbers of soldiers being sent north in 1763. Though driven by the desire to save costs, the letters detailing this arrangement also indicate a belief that the resulting accommodation would be 'very neat, and answer the purpose abundantly well' (Millar, 1909, 83).

Encouragements to build 'better' houses partly manifested in the emergence of planned villages in the Highlands under the auspices of organisations like the British Fisheries Society. This society came into being to exploit vast marine resources such as herring and sought to help tame the wild north-west 'frontier' through the establishment of Ullapool in 1787 and Tobermory in 1789. These settlements provided a template for new planned towns over the coming decades and were built with stipulations designed to eradicate traditional vernacular building practices. These sought to ensure uniformity of standard and regularity in layout and achieved a high level of success, in some places demonstrating the efficiency with which vernacular traditions could be replaced (Maudlin, 2004). In spite of such developments, however, there remains a great deal of late-eighteenth and nineteenth century evidence for the continued existence and erection of mudwall buildings. Lockhart (2001), for example, previously highlighted evidence for the reservation of villagers' rights to dig clay for building from the uncultivated commonty lands that associated planned villages in the north-east, of which around one hundred were established between 1750 and 1850.

The history of Scottish mudwall building is far longer than would appear if one took the number of remaining examples as reflecting original quantity, a drawback that also serves to undermine the reliance on field survey that has hitherto dominated studies of Scottish earth building. There are records for the demolition of fifty-nine clay dabbins in Cumbria since the Second World War, before which time the majority of earth buildings would have already been replaced, and it can be readily perceived that many more were lost in this later period without documentation (Oxford Archaeology North, 2006). The recorded demolition of a mudwall farmhouse on Ministry of Defence land at West Freugh, Wigtownshire (Fig. 4.16), testifies to this process on the Scottish side of the border (Oxford Archaeology North, 2005), as does the case of a claywall structure at Upper Haugh, Aberdeenshire (Fig. 4.17). Archaeological evidence also points to the establishment of new, though short-lived, settlements being built using clay and bool in Morayshire in the mid-nineteenth century (Murray, 2007-8). In Stranraer and the south-west more generally there are numerous unrecorded and recently lost mudwall dwellings (Adderley, Parkin and McLaughlin, forthcoming).

Fig. 4.17. West Freugh Farmhouse before and during demolition in 2004. (Images courtesy of Stranraer Museum).

Fig. 4.16. Demolition of claywall building at Upper Haugh, Aberdeenshire, recorded by the RCAHMS in 2003, with the somewhat ironic note 'apparently during demolition'. (© Crown Copyright: RCAHMS. Licensor: www.rcahms.gov.uk).

Statements regarding the replacement and improvement of the building stock are found repeatedly over a near thirty year period from the mid-1790s within the *General Views*. Nonetheless, sympathetic accounts of traditional methods can be found from within the same body of works. Souter's *General View* of Banffshire, 1812, follows the typical line in stating that 'very considerable improvements have, within these last thirty years, taken place in the erection of farm-houses and offices'. He noted that many farmhouses were 'built of stone and clay mortar, having the joining of the stone neatly closed with lime mortar'. This explanation leads to a footnote in which it is explained that

'In several places in this county the walls of houses and cottages have been built of a composition of mud or clay, mixed with small stones and straw, called *Auchenhalrig Work*.

This kind of wall has been recommended for farm-steadings, in situations where stones are not easily procured, and is said to be cheap, substantial, and durable' (Souter, 1812, 89-92).

This stands out as a noticeably more pragmatic approach to the assessment of a type of massed earth construction that was idiosyncratic to its locality (Fig. 4.18). Furthermore, Souter provides, in his second appendix, a comprehensive description of the construction process as would be entailed in building a 'rood of thirty-six square yards'. The account continues in glowing terms, the reporter stating that when

'finished, the Auchenhalrig houses are, out and inside, as ornamental as those built entirely of stone and lime mortar… particularly adapted for dwelling houses, of two stories, and merits attention on account of its cheapness, durability, and warmth, as it excludes every breath of air. The workmanship of a rood costs only about one pound three shillings, and will, when properly built, and well kept under thatch, last for more than a century. Of this there can be no doubt, as in the village of Garmouth, in Morayshire, there are several houses built of these materials, and covered with slate, which have stood upwards of a hundred years, and are at present in excellent condition' (Souter, 1812, Appendix II, 9-11).

The account reads as an almost eulogising assertion and places emphasis on what are presently seen as some of the most redeeming features of mass earth construction that have reinvigorated the interest of contemporary builders and architects.

Fig. 4.18. Auchenhalrig structure (note the clay thatched roof), Cowfurach, Banffshire (Photo taken by P.J. Nuttgens in 1956 and held by the School of Scottish Studies Archive, University of Edinburgh).

Building in earth continued well into the nineteenth century in Scotland, in spite of the influence that Improvement had on the erosion, physically and metaphorically, of such practices. The combination of vernacular materials in professionally constructed buildings has precedents both documentarily and in surviving example, such as a missive letter dating to 1789 relating to the building of a 60 foot (c. 18 m) long house in Tain built with 'solid mud, except the corners, door, and window skimshions, Lintols and soles, chimney and chimney heads, Sque and wall tabeling, all of which is to be of the best quarry stones neatly hewed' (MacGill, 1909, 195-6). This surely reflects a perception of mudwall as being of good quality, depending on context, the reputation of the builder and prospective inhabitants. Furthermore, the combined use of a vernacular material with high quality building stone encapsulates a transitional period in which the influence of Enlightenment thought was reflected in the built environment. An interesting case study for the meeting of traditional and contemporary approaches to construction can be found in the upper part of the village of Moffat in Dumfries and Galloway, where two houses from around 1750 escaped the process of town improvement imposed by the Earl of Hopetoun following his acquisition of the Upper Annandale Estate in 1758. The Earl sought to replace the vernacular housing stock with dwellings built in stone and lime, with slated roofs, and this process was largely carried out between 1765 and 1790. The houses of John Black and Archibald Moffatt were, however, held privately and avoided the Earl's interference (Elliot, pers. comm.). These buildings now remain as intriguing contradictions, with their outward appearance of urban respectability through contemporary design belying internal walls of field boulders set in clay soil (Fig. 4.19).

Fig. 4.19. Left: 'Archibald Moffatt's House', Moffat, Dumfries and Galloway. Right: Exposed mud and boulder wall behind original plaster. (Photo credit: Niamh Elliot).

The *Statistical Account of Scotland* was published in twenty-one volumes between 1791 and 1799 and this was followed by the fifty-two parts of the *New Account* in the years between 1834 and 1845 (see Withers, http://edina.ac.uk/stat-acc-scot/reading/intro.shtml, for a short introduction). Both were compiled as a means of describing and quantifying the state of the nation using much the same format and can thus provide a bookended insight into perceptions of mudwall building between the late-eighteenth to mid-nineteenth centuries. An entry for Campbeltown, Argyll, in the *Old* accounts highlights the aspirations of Improvement as the reporter refers to the abundance of clay and coal as a commercial opportunity awaiting exploitation through the manufacturing of roof tiles for the Glasgow market. Simultaneously, it is suggested that this could benefit local farmers as they would no longer need to expend straw and labor on thatching, whilst also improving the 'cleanliness or comfort' of their dwellings (Sinclair, 1791-99, **10**, 565). In contrast, some entries demonstrate that mudwall dwellings were not always disregarded and refrain from demanding their replacement. Mudwall dwellings in Elgin, sometimes two stories tall, were deemed comfortable and durable (Sinclair, 1791-99, **14**, 390). For Dornock, in Dumfriesshire, emphasis was also placed on the quality of living that could be provided by mudwall homes, which were built efficiently through community involvement (Sinclair, 1791-99, **2**, 22). That the 'whole neighborhood' could assemble to help in the building process demonstrates the unspecialised nature of the building method, allowing all parties to help in some form or another to achieve a more than acceptable result, even according to an outside perspective. Clearly it would be best to avoid thinking of such activities as reflecting some kind of collectivist utopia, but the social element of vernacular construction, still known in places with living traditions in earth building, certainly seems worth appreciating. Conversely, the report given for Penninghame, not far from Dornock in the County of Wigtown and of comparable geological context, asserts that the population was the 'healthiest in the parish' in spite of their homes (Sinclair, 1791-99, **3**, 343). The inconsistency of opinion towards mudwall dwellings could reflect variation in the quality of construction from place to place, the varying degrees to which individual reporters adhered to the Improvement agenda, assertion of personal opinion or a combination of all such factors.

By the time of the *New Statistical Account*, there is greater uniformity between reports on building quality in the rural setting. The continued improvement of the building stock with stone, lime and slated roofing is lauded, whilst mudwalls receive less favorable reviews than in some of the *Old* accounts. The interim period between the *First* and *Second Accounts* for St Mungo (Society for the Benefit of the Sons and Daughters of the Clergy, 1845, **4**, 217) and Cummertrees (Society for the Benefit of the Sons and Daughters of the Clergy, 1845, **4**, 255) in the country north and west of Dornock and Peningham, respectively, is said to have seen the replacement of all mud with stone and lime; Dundonald in Ayrshire saw a similar process in the replacement of mudwalls with 'in many places... elegant architecture' (Society for the Benefit of the Sons and Daughters of the Clergy, 1845, **5**, 688); Dolphinton, in Lanarkshire, saw the removal of a 'wretched' landscape in which people dwelt in mudwalled, turf-roofed houses (Society for the Benefit of the Sons and Daughters of the Clergy, 1845, **6**, 59); and in Turriff, Aberdeenshire, the farmers' houses and buildings had all become stone and lime with slates, although the cottages remained 'of mud, ill-constructed, ill-ventilated, and ill-roofed' with notable exception afforded to those with 'well-swept hearth and white-washed wall and sanded floor, [which] give an air of comfort and contemtment exceedingly pleasing' (V, 1845, **12**, 1002). The persistent use of mud mortar in building 'open' and 'damp' dwellings in both Eckford and Sprouston, Roxburghshire, was associated with a variety of 'distempers' including 'fever, pulmonary complaints, and rheumatism' (VI, 1845, **3**, 236), although in Lochs, in the County of Ross and Cromarty, the same materials were reserved for the three best dwellings of the parish, with the remaining collection being deemed 'wretched… built of stone and moss; but mostly of moss… Their upper ends are occupied by the families, and their lower ends by their cattle, without any partition or division between them' (VII, **14**, 164). Clearly, the perception of vernacular materials was partly dependent upon expectations in relation to people and place.

The trend to perceive vernacular earth-built dwellings negatively diffused into the twentieth century, although not as a blanket view. Hutcheson's *Old Stories in Stone and Other Papers*, for example, specifically equated the 'clay biggins' of rural Scotland with the intellectual inferiority of their inhabitants to the point to which they represented 'not a going back to barbarism, but an absolute non-advance from barbarism' (Hutcheson, 1927, 85). The lost irony of this assertion is earlier established, however, through reference to one of Scotland's most intellectually celebrated sons, Robert Burns, and his being born in the same type of 'clay biggin' as those rural dwellers disregarded as being absent 'of all the arts of civilisation and literature' (Hutcheson, 1927, 40). Conversely, the celebration of Burns by some of Hutcheson's contemporaries led to a degree of romanticisation of his humble upbringing and this perhaps influenced later interest in recording and conserving vernacular structures. The romanticisation of the vernacular is encapsulated in Sinclair's *The Thatched houses of the Old Highlands* (Sinclair, 1953) and an edited volume, the *Auld Clay Biggin* (Ross, 1925a), sought to celebrate the birthplace of the national bard. The collection of poetry and prose in this emphasises the synonymy of Burns' egalitarian views with his first home, which was typical of the 'common man', contrasting this with the two-storey house of Shakespeare, the 'middle class' national bard for England.

'Burns was born in a mud-walled cottage, about as humble a habitation as could be found in Scotland; and poverty, hard and unending toil were the things he was most acquainted with when he began his life's journey. The cottage still stands near the now classic Doon, and is in itself a silent but significant tribute to his genius… John Murdoch said:- 'It was, with the exception of a little straw, literally a tabernacle of clay. In this mean cottage, of which I myself was at times an inhabitant, I really believe there dwelt a larger portion of content than in any place in Europe. The ‘Cotter’s Saturday Night’ will give some idea of the temper and manners that prevailed there’’ (Ross, 1925b, 49-50).

4.8 Conclusion

This discussion has sought to engage further with documentary and archaeological evidence in order to emphasise the medieval ancestry of Scotland’s extant eighteenth, nineteenth and twentieth century mudwall buildings, underlining the importance of these sources alongside the evidence of surveys that has been thus far relied upon. Such survey evidence has previously skewed perceptions of earthen materials and techniques across Britain and Ireland through the implication that non-survival indicates poor-quality and impermanence rather than neglect or removal. Nevertheless, vernacular mudwall structures were ubiquitous in Scottish landscapes for centuries and the limited archaeological evidence currently available in Scotland suggests that advances in building practices in the medieval period may have been key to the proliferation of the technique. After all, it was surely favourable to utilise clay-rich subsoils, which produced homes with favorable thermal qualities, wherever local deposits allowed.

That enclaves of historic vernacular mudwall buildings survive in the landscapes of northern Britain, despite targeted and sustained efforts at their removal from the Improvement era onwards, demonstrates the longevity with which these structures of medieval descent could stand. Verification for this point is found in the remaining clay dabbins of the Solway Plain, some of which have stood for over five centuries despite human encroachment and the notoriously wet climate of western Britain. Mudwall buildings of such date are unknown in Scotland, but the still-standing eighteenth and nineteenth century dwellings and agricultural buildings of the Carse of Gowrie, north east and south west remain as vestiges of a much deeper tradition. Furthermore, although the prior ubiquity of Scotland’s mudwall buildings has been appreciated for a significant period of time, the early-eighteenth century Bannockburn papers provide an invaluable source of evidence to emphasise the point that this building technique was so relied upon to develop the building stock of a pre-Improvement estate.

Traditional narratives relating to Scotland's earth building traditions retain pertinence but it has been highlighted here that they must also be accompanied by a greater appreciation of earlier perceptions and definitive proof of past proliferation, in order to fully appreciate the significance of all-but-lost associated crafts. The vernacular buildings of the rural majority were negatively perceived for a number of centuries prior to the period of Improvement by some alien commentators who starkly contrasted their own self-determined civility with the barbarity of those who lived in homes of mud. It must be remembered, however, that many commentaries were influenced by politically motivated vested interests, which encouraged medieval visitors from England and the continent to emphasise the uncouth nature of Scotland's society. Nevertheless, references to the backwardness of Scotland's rural population persisted with some regularity through the centuries and were often associated with the built environment. It is also worthy of note that negative perceptions of dwellings were related to more than just the materials used in construction.

Surviving evidence in the structures built by social elites in medieval Britain reveals a contrasting and pragmatic approach to the use of earthen building materials at the local level, as demonstrated by the presence of mud mortars, earthen partition walls and turf ancillary structures at castle sites, for example. From the mid-eighteenth century, however, Scottish elite society was increasingly concerned with the unequivocal replacement of the vernacular building stock, a mission that achieved great success and contributed to the loss of longstanding craft traditions. This centered on notions of the need for modernisation, bringing marginal peoples and regions closer to the political centre and in line with the rational thought of the day as a means of encouraging the economic and social development of the nation. The

Statistical Accounts testify to the gradual replacement of mudwall buildings, although the process was somewhat piecemeal and often meant the facing of mudwall with another material to give the image of modernity or the continued application of mud mortar in spite of stipulations in favour of lime. The impact of Improvement ideology and the associated physical and social reorganisations that took hold from the eighteenth century saw a drastic downturn in the employment of earth-building practices in Scotland and ultimately led to the loss of a vernacular building tradition whose geographically widespread history was far longer and more socially significant than would appear if one took the number of remaining examples as reflective of their original quantity. In turn, this transitional phase solidified a growing trend to perceive earth-built structures in a negative light, with connotations of backwardness and poor health of populations being bound to the homes in which they lived.

This first part of this thesis has sought to emphasise the value of Scotland's surviving earth-built heritage as the embodiment of lost craft practices inherited over time from deep within cultural history and as an integral part of the wider global tradition touched upon in the first instance. It seems that the under-valuation of Scotland's earth-built heritage has in part been the product of inherited perceptions that are unlikely to have been representative throughout much of the time that vernacular earth building methods were popularly employed.

Climate change and the earth-built heritage

5. Climate change, heritage climatology and climate cabinet experimentation

5.1 Introduction

The research conducted by climate scientists over a number of decades has led to international consensus that human activities have contributed greatly to the climate changes observed for the twentieth century (rather than these just being a product of natural climate variability over geological time), notably through the emission of greenhouse gases (GHGs) and changes to land-use. Furthermore, it is generally agreed that with the continuation of current global socio-economic conditions these climatic changes would continue to intensify over the twenty-first century, reaching unprecedented levels, and that mitigation strategies are required for the safeguarding of global environments and societies in the widest sense. This consensus at the levels of international community and national government is of great relevance to this thesis as climate impacts become ever more prominent drivers of heritage policy in the United Kingdom.

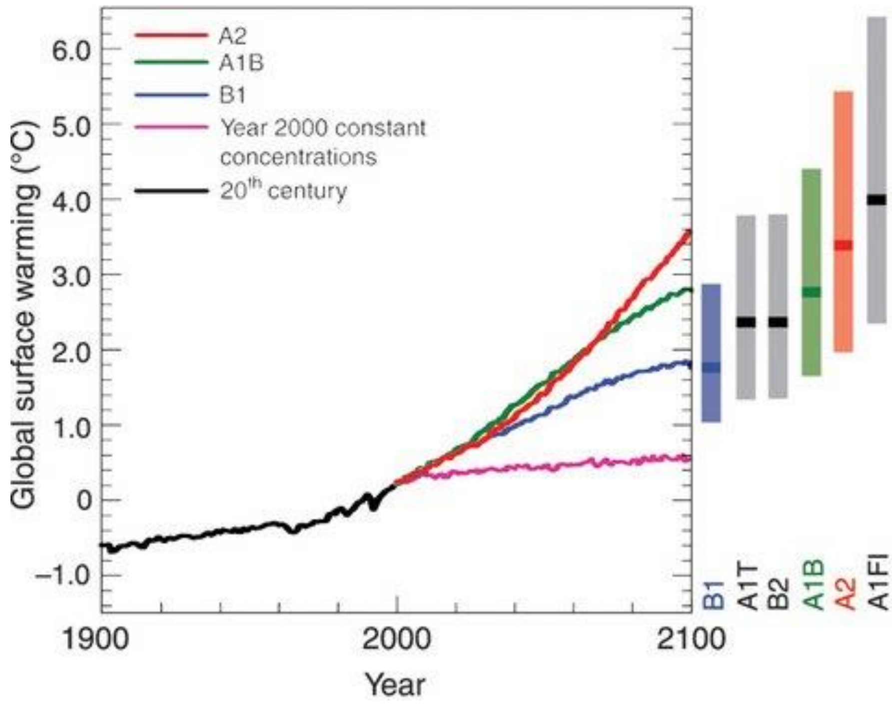


Fig.5.1. Observed warming of global temperature since 1900 and projections of future warming for the remainder of the twenty-first century based on six different IPCC emissions scenarios. After Fig. 3.2 of *Climate Change 2007: Synthesis Report* (IPCC, 2007a, 46). © IPCC.

5.2 Climate change and climate modelling

Climate science is an almost infinitely complex and ever-evolving forum of research, which cannot be elucidated upon within the scope of this thesis beyond general summarisation. Current understandings of climate change have been built upon foundations laid in geological and palaeontological studies of the nineteenth and twentieth centuries. From this, palaeoclimatic understandings have developed with gathering pace since the 1950s. Thus, the great variability of the earth's past climate has long been recognised, establishing the notion of assessing current and future conditions through knowledge of those in the past (Le Treut *et al.*, 2007). The definition and understanding of known baseline conditions and the systems by which they were created therefore provides the fundamental starting point for assessing the impacts of the cyclical relationships between human activity and recent and future climate. It is generally agreed within the scientific community that anthropogenic impacts on climate pivot around the emission of GHGs, particularly carbon dioxide (CO_2), in inexorably higher amounts since the onset of industrialisation in the mid-eighteenth century (Eggleton, 2012).It is also agreed that even if GHG emissions were held at levels observed in 2000, global temperatures would continue to rise by 0.1°C for each of the next two decades (IPCC, 2007b). Since the mid-nineteenth century mean global temperature has increased by 0.8°C, with a doubling in the rate of change for the last fifty years up to 2006 in comparison with the preceding fifty. Mean global precipitation has increased since 1900 in areas above 30°N, although similar increases between 10° and 30°N have stalled since about 1970. Decreases in precipitation have been observed between 10°N and 10°S, with these particularly apparent after the mid-1970s, coinciding with increased occurrence of droughts in the tropics and subtropics. Increased incidence of heavy and rare rainfall events have been observed as a global trend over the piece (Trenberth *et al.*, 2007). GHG emissions have continued to rise since 2000 and emissions of CO_2 have been estimated by the IPCC (2007c) to rise by between 40 to 100% by 2030 if current energy and development policies are maintained. This highlights the importance of developing effective climate mitigation strategies in the short-, medium- and longer-term. Appropriate adaptation strategies to ensure the protection of culturally valuable properties and artefacts are therefore integral to the objectives of such long term mitigation (Cassar, 2010).

5.2.1 IPCC reports and emission scenarios

The *Intergovernmental Panel on Climate Change* (IPCC) was established in December 1988 through the *World Meteorological Organisation* (WMO) and the *United Nations Environment Program* (UNEP) with the mandate to assess 'available scientific information on climate change' and its 'environmental and socio-economic impacts' in order to 'formulate realistic response strategies' (IPCC, 1990, Preface). The *First Assessment Report* (IPCC, 1990) was delivered in 1990 and has been followed so far by three more, in 1995, 2001 and 2007, which have been punctuated by regular supplementary reports. The first part of a *Fifth Assessment Report* was published in 2013, with the following parts released in 2014. These reports provide the most comprehensive collation of peer-reviewed scientific research into climate change and demonstrate the incremental advances in scientific understandings of past variability and future projections. The projections are synthesised from data generated by numerous models around the globe and are given as a range of likelihoods depending on different emissions scenarios, based upon the means and variability of weather phenomena over thirty-year periods. This follows the example of the World Meteorological Organisation (http://www.wmo.int/pages/themes/climate/climate_data_and_products.php). Such thirty-year blocks are deemed sufficiently long to smooth out interannual deviations and sufficiently short to highlight trends in climate over lengthier time periods. Future projections are set against baseline, or 'normal', conditions, which are provided by observed data and modelled conditions from 1961 to 1990. The scenarios upon which projections are based were first developed by the IPCC in 1990 before being updated and outlined in 2000 in the *Special*

Report on Emissions Scenarios (SRES) (IPCC, 2000), which sought to 'reflect current understanding and knowledge about underlying uncertainties'. The scenarios are based on four primary narratives developed to describe the potential extents of future warming, depending upon the greatly varying impacts of demographic, social, economic, technological, and environmental factors on GHG emissions. Thus, the four distinct narratives represent individual scenario 'families', across which six scenario groups (A1F1, A1T, A1B; A2; B1; and B2) are spread. Within these groups are a variety of forty different scenarios, twenty-six of which are based on common assumptions of global population and economic development (harmonised scenarios) and fourteen of which are based on alternative interpretations of the narratives and the possibilities of contributing uncertainties. The full descriptions of the narratives and scenarios are set out for policy makers as follows:

The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1F1), non-fossil energy sources (A1T), or a balance across all sources (A1B).

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A l storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels. (IPCC, 2000, 4-5)

The climate change consensus encapsulated in the IPCC reports is defined by general agreement amongst climate scientists that atmospheric warming is occurring and will continue to occur in line with future CO_2 emissions, rather than absolute accord over the extent to which changes will occur into the future. Thus, estimates are given within a range of possibilities and account for the different future scenarios outlined. For descriptive purposes the IPCC reports refer to the statistical likelihood of projections as between ‘extremely unlikely’ and ‘virtually certain’, with demarcations based upon percentages groups as follows:

Virtually certain > 99% probability of occurrence, Extremely likely > 95%, Very likely > 90%, Likely > 66%, More likely than not > 50%, Unlikely < 33%, Very unlikely < 10%, Extremely unlikely < 5% (Solomon, *et al.*, 2007, 22-23)

5.2.2 Global climate projections

Estimates of global projected temperature increases by 2090-99 lie between 1.1°C and 6.4°C, depending upon the emissions scenario modelled, with 2°C to 4.5°C deemed a *likely* range (Meehl *et al.*, 2000). Some of the most notable related consequences of this warming process, which themselves have complex feedback mechanisms, have been summarised by the IPCC. It is *very likely* that heat waves will be exacerbated in the future; minimum daily temperatures will increase quicker than daily maximums, reducing diurnal temperature ranges and the frequency of frost events. Globally, mean precipitation is projected to increase, although with variation across the high latitudes, tropics and subtropics, the latter of which will see mean precipitation decrease. The intensity of precipitation events is projected to increase at a greater rate than the mean in the high latitudes and tropics. Summer droughts are also expected for mid-continental areas. Ice and snow at sea and terrestrially is projected to continue melting across the twenty-first century, with the corollary of continued rises in sea level. Such rises in sea level will vary around the globe and are highly dependent upon the emissions scenarios, with mid-century average projections suggesting sea level rise of between 0.02 m and 0.15 m by 2090-99. It is *very likely*, however, that rises will continue to exceed those of the late-twentieth century (1.8 ± 0.5 mm yr^{-1}), regardless of the scenario model. Numerous further impacts are explained, including changes to the carbon cycle, sea level pressure, tropical cyclones, mid-latitude storms, Meridional Overturning Circulation (MOC) of the Atlantic, surface warming of the north Atlantic and radiative forcing, all of which stimulate further myriad environmental effects (Randall *et al.*, 2007).

5.2.3 Regional climate projections

Of most importance here, however, are increasingly localised projections based on multi-model data sets (MMDs) and Regional Climate Models (RCMs), from the European continental scale to that of the United Kingdom. This ultimately leads to the further downscaling of modelled data conducted as part of the research for this thesis, for the purposes of identifying risk factors relevant to Scotland's earth-built heritage and to inform climate cabinet experimentation. This is returned to in Chapter 6. The IPCC summarises European climate projections as including a number of variations from the global mean projections. These include temperature increases in Europe greater than the global mean, relative to the scenarios modelled. As expected on the global scale, heat waves are projected to become more common, more extreme and longer and frost days are liable to decrease notably. Mean precipitation is projected to increase in northern Europe, particularly during winter, but decrease across most of the Mediterranean. Central Europe is liable to experience increased winter precipitation but decreased summer precipitation. Extreme rainfall events are projected to become more frequent and intense where mean winter precipitation increases (Christensen *et al.*, 2007).

5.2.4 UK climate projections

The UK Climate Projections (UKCP09) dataset provides national- and sub-national scale climate projections and is used to drive climate change mitigation policies in the United Kingdom, being funded by the United Kingdom Government and devolved administrations through the Department of Environment, Food and Rural Affairs (DEFRA), Department of Energy and Climate Change (DECC), the Department of Environment Northern Ireland (DOENI), the Scottish Government and Welsh Assembly Government (http://ukclimateprojections.defra.gov.uk/). As part of the basis for this, the historically observed climate trends for the United Kingdom have been summarised by Jenkins *et al.* (2009) on behalf of UKCP09. Based on the Central England Temperature (CET) series, the longest unbroken set of temperature records in the world, dating back to 1659 (Manley, 1974), historical inferences can be justifiably gained for the United Kingdom as a whole (Croxton *et al.*, 2006). This record indicates a rise in mean annual temperature in the order of around 2°C between 1850 and the present, with rapid acceleration of this increase being observed from the 1980s onwards.

5.2.5 Scotland's climate and past weather data

Scotland has a maritime climate regime punctuated by frequent (intra-daily or weekly) changes between mild warm and dry conditions to mild warm and damp conditions. Detailed historic climate records for Scotland date to 1757 and climate changes since then can be evaluated relative to long-term mean values. Mean annual precipitation was relatively consistent compared to the long term mean until the 1970s, since when substantial increases have been recorded (Smith, 1995). Localised shifts in weather patterns have been observed alongside annual nationwide increases in rainfall, with especially pronounced seasonal shifts in some regions (Mayes, 1996). Comparison of monthly climate normals over 30-year periods in the twentieth century provides evidence of winters having become wetter concurrently with dryer summer periods. Jones and Lister (2004) augmented the CET data with their distillation of a national monthly temperature series for Scotland (separated into mainland and island [Orkney, Shetland and the Outer Hebrides] zones) and Northern Ireland from various data sources. This work demonstrates that from 1861 to 2000 the mean annual temperature of the Scottish mainland increased 0.69°C, that of the Scottish islands by 0.64°C and by 0.77°C in Northern Ireland, with accelerated increases in the rate of warming having occurred since the 1980s, similarly to the CET. Annual precipitation levels have remained fairly constant over the observed period, but from 1766 in England and Wales and from 1931 in Scotland, a trend has emerged across most of the United Kingdom for greater seasonality in rainfall. Increased winter precipitation has been witnessed as a consequence of more frequent extreme events alongside decreases in summer precipitation (Jenkins *et al.*, 2009).

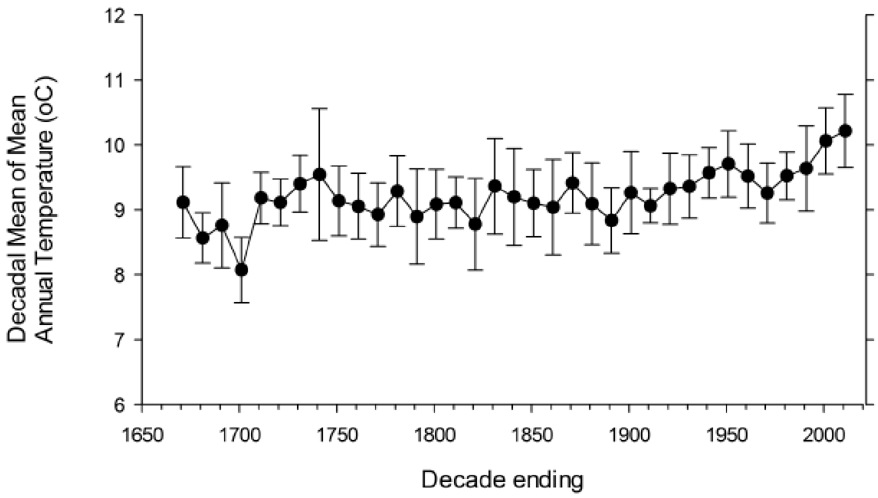


Fig. 5.2. Observed decadal mean temperatures from the seventeenth century onwards, using CET data.

5.2.6 UKCP09 projections

UKCP09 uses three of the SRES scenarios outlined by the IPCC alongside UK-focused climate science in order to project climatic changes resulting from high (SRES A1F1), medium (SRES A1B) and low (SRES B1) emissions scenarios over the course of the twenty-first century. The projected climate data provided by UKCP09 are the product of a number of climate models including the Met Office Hadley Centre Global Climate Model (HADCM3), an ocean-atmosphere GCM recognised by the IPCC and used in its collaborative modelling activities. The UKCP09 data are given at a resolution of 25 km^2 and are summarised graphically online for seven consecutive, overlapping thirty-year periods spanning 2010 to 2100, in conjunction with the modelled baseline data. The projections are given for sixteen designated administrative regions of the United Kingdom and indicate significant variability between the more disparate locations. Murphy *et al.* (2009) provide the summary of how UKCP09 climate projections are designed and the theories, methods and limitations involved in their generation. This latter point is qualified by the acknowledgement of uncertainties relating to future natural variability, imperfect understandings of climate systems and their replication in models and the unknown extents of future GHG emissions. A range of climate variables for land areas and marine regions are considered in the projections, with the former being of most interest here, including mean temperature, mean daily maximum and minimum temperature, precipitation rate and relative humidity. Amongst the typical findings of UKCP09, within the context of variability across the regions, are increases to both daily minimum and daily maximum temperatures, limited change to annual mean precipitation but with increases to winter precipitation and decreases in summer precipitation and decreases in summer relative humidity (Jenkins *et al.*, 2009). UKCP09 also provides a 'Weather Generator' downscaling tool, allowing users to model the included variables at a more localised scale. This tool was used as a means of generating projected climate scenarios specifically for the Carse of Gowrie, in Perthshire, an area that retains a significant number of extant earth-built structures and the focus of field sampling activities related to this thesis. The outcomes of these activities are elucidated in Chapters 7 to 10.

5.3 Climate change and cultural heritage

Before irreversible damage is done, concerted actions based on sound science, are needed to protect, strengthen and adapt Europe's unique cultural patrimony (Sabbioni *et al.*, 2010, Preface)

The extents of impacts resulting from climate change and associated factors depend upon global, inter-regional, intra-regional or more localised, as well as temporal, variability. This means that mitigation strategies must be developed at international, regional, national and local scales and account for generational boundaries (Gupta *et al.*, 2007). As discussed, the impacts of continued climate change are incredibly wide-ranging and include a variety of feedback mechanisms that could cyclically aggravate other fundamental natural and anthropogenic drivers. A range of climate change implications have been summarised by the IPCC, although the scantiness of references to cultural heritage (particularly built heritage) impacts in the reports is noteworthy (IPCC, 2007a; IPCC, 2007b).

5.3.1 Policy, research and heritage climatology

Acknowledging the implications of the IPCC reports, heritage custodians have become increasingly aware of present and potential future climate-related impacts upon cultural heritage, with such concerns now being central to the remit of caring for properties. As such, there is increased emphasis placed upon proactivity with regards to the conservation of cultural heritage (Historic Scotland, 2012), with recognition of the likelihood of new or altered damage functions related to continued climatic and environmental changes at the centennial scale. This is reflected in investments in research since the turn of the millennium. English Heritage marked growing concerns over the potential impacts of climate change in its *State of the Historic Environment Report 2002*:

‘Climate change is an acknowledged threat to both the natural and the historic environment. For example, changes in the intensity and frequency of storm events will pose a challenge to a wide spectrum of the historic environment from coastal sites to veteran trees. Can we measure the likely impact and cost the necessary mitigation?’ (English Heritage, 2002, 6).

The direct effects of climate on the built environment have been recognised for centuries, as encapsulated in the longstanding use of the term ‘weathering’. So too has the human element within this, as the aesthetic and deteriorative impacts of burning of fossil fuels, causing the blackening of stone by air-borne particulates in urban contexts, was noted by commentators across Europe from classical times (Sabbioni *et al.*, 2006; Brimblecombe *et al.*, 2006b; Brimblecombe and Grossi, 2009). Many of the consequences of the observed climate changes driven by the burning of fossil fuels from the mid-nineteenth century take a more indirect avenue to impacting the built heritage, however. This has formed the basis for various initiatives run in parallel across Europe over the last decade or so. Exploratory research undertaken at University College London (Cassar, 2005) sought to provide answers to the question posed above, subsequently leading to the publication of *Engineering Historic Futures:*

Stakeholders Dissemination and Scientific Research Report (Cassar and Hawkings, 2007) and informing English Heritage's *Climate Change and the Historic Environment* (English Heritage, 2006 [updated 2008/2012]). In 2004 the pan-European NOAH's ARK project was established and built upon the emerging consensus of a need for closer links between climate science and heritage, seeking to assign recent past, near future and far future climate parameters with levels of risk to the extant and archaeological heritage of Europe (Sabbioni and Bonazza, 2010). A number of scientific publications emanated from the research activities central to the project (Sabbioni *et al.*, 2006; Brimblecombe *et al.*, 2006a; Grossi *et al*., 2007, for example) and the primary outcomes have been published in the form of risk maps in *The Atlas of Climate Change Impact on European Cultural Heritage* (Sabbioni *et al.*, 2010). In 2006 a meeting of the World Heritage Committee led to UNESCO's *Climate Change and World Heritage* report (UNESCO, 2007), which highlighted potential physical (or natural), cultural and social consequences of continued climate change (Table 5.1). This highlighted a range of fundamental climate parameters and associated risk factors, as used within the NOAH's ARK project, in relation to the deterioration of cultural heritage. Included in the relevant parameters are atmospheric moisture change, temperature change, sea level rises, wind, desertification, climate and pollution interaction and biological effects. It is the first two of these parameters that are deemed of most interest here. The Scientific Council of the International Council on Monuments and Sites (ICOMOS) has also established an interdisciplinary research agenda seeking to outline global climate change impacts on tangible and intangible heritage (ICOMOS, 2008).

The objective of the NOAH's ARK project to 'research, predict and describe the effects of climate change on Europe's built cultural heritage over the next 100 years' (http://noahsark.isac.cnr.it/overview.php) neatly encapsulates the context for the technical aspects of the research from which this thesis stems, providing a key avenue through which to encourage the inclusion of earthen materials in the mainstream of heritage discourses. Based on the IPCC SRES A2 storyline, *The Atlas of Climate Change Impacts* identifies specific climate-related risk factors at the continental scale, within the observable and modelled parameters used in climate studies, to aid built and archaeological heritage policy development. This approach has been informed by the development, as an inherent part of the project's research, of heritage climatology as a sub-disciplinary field of climate science. This seeks to relate projected changes to specific climatological parameters to the performance of heritage materials, including the understanding of periods of exposure and quantifiable levels of damage (Brimblecombe, 2010). It is essential that such approaches are led by a sound understanding of climate-related risk factors pertinent to building materials in the present, with the notion that assessments can be made as to how these may change into the future depending upon site-specific contexts. For example, although increasing temperatures over the course of the twenty-first century in Europe may mean a reduction in the number of freeze-thaw cycles and therefore a reduction in cases of frost shattering in porous building stone, the same climatic change may result in the thawing of archaeological sites in the northern latitudes with corollary effects on preservation of buried materials (Sabbioni *et al.*, 2010).

Table 5.1. Extract from *Climate Change and World Heritage* (UNESCO, 2007), with aspects of most interest to this thesis in bold.

Climate indicator	Climate change risk	Physical, social and cultural impacts on cultural heritage
Atmospheric moisture change	• **Flooding** (sea, river) • **Intense rainfall** • **Changes in water table levels** • Changes in soil chemistry • **Ground water changes** • **Increase in time of wetness** • Sea salt chlorides	• pH changes to buried archaeological evidence • Loss of stratigraphic integrity due to cracking and heaving from changes in sediment moisture • Data loss preserved in waterlogged / anaerobic /anoxic conditions • Eutrophication accelerating microbial decomposition of organics • **Physical changes to porous building materials and finishes due to rising damp** • **Damage due to faulty or inadequate water disposal systems**; historic rainwater goods not capable of handling heavy rain and often difficult to access, maintain, and adjust • **Crystallisation and dissolution of salts caused by wetting and drying affecting standing structures**, archaeology, wall paintings, frescos and other decorated surfaces

		• Erosion of organic and inorganic materials due to flood waters • Biological attack of organic materials by insects, moulds, fungi, invasive species such as termites • Soil instability, ground heave and subsidence • **Relative humidity cycles / shock causing splitting, cracking, flaking, and dusting of materials and surfaces** • Corrosion of metals • Other combined effects, e.g. increase in moisture combined with fertilisers and pesticides
Temperature change	• **Diurnal, seasonal, extreme events** (heat waves, snow loading) • **Changes in freeze-thaw** and ice storms, and **increase in wet frost**	• Deterioration of facades due to thermal stress • **Freeze-thaw / frost damage** • **Damage inside brick, stone, ceramics that has got wet and frozen within material before drying** • Biochemical deterioration • Changes in 'fitness for purpose' of some structures. For example overheating of the interior of buildings can lead to inappropriate alterations to the historic fabric due to the introduction of engineering solutions • Inappropriate adaptation to allow structures to remain in use

Various authors have contributed to quantifying specific processes of materials' deterioration, whether in terms of acceleration or deceleration (Sabbioni *et al.*, 2006), that stem from considerations of the factors listed above. Notably, *The Atlas of Climate Change Impacts* includes dedicated sections on stone and brick, wood and metals but not earth. Brimblecombe and Grossi (2007) have noted that small temperature changes (of two or three degrees Celsius, for example) may not carry a direct threat to the structural properties of materials used in construction, but the implications of this for changes to the frequency of freeze-thaw or wet-dry cycles carries ramifications, depending on location, due to the precise temperature at which a specific phase change may occur. Grossi *et al.* (2007) have considered the implications of projected changes to annual temperature for the frequency of freeze-thaw cycles and corollary impacts on the built and archaeological heritage around Europe. They emphasise that granular disintegration and flaking induced by ice segregation in rocks occur at between -1°C to -4°C, depending on porosity, and note that the exacerbation of already extant fractures occurs at marginally less than 0°C. Therefore, 0°C is deemed the critical temperature used to determine the frequency of freeze-thaw cycles within a given time period, depending on the number of times temperature oscillates either side of this point. From this, it is concluded that general warming should produce fewer freezing events around much of Europe, reducing stresses for the built heritage in many areas. Simultaneously, however, this increases the possibility of archaeological deposits thawing in the far north, causing the decay of organic materials, for example. The repercussions of even slight changes to relative humidity in relation to salt damage have also been demonstrated, with sodium chloride solution crystallising at 75.3±0.5%, for example, irrespective of temperature (Sabbioni *et al.*, 2010). Decreases in relative humidity projected across Europe over the remainder of the century suggest that this is likely to result in increased incidence of such a phase change occurring within porous building media (Brimblecombe and Grossi, 2007; Grossi *et al.*, 2011), internal historic environments and artefacts (Lankester and Brimblecombe, 2012). Brimblecombe *et al.* (2006b) have also considered changes to the time of wetness at the surface of building materials, associated with myriad causes of deterioration across the seasons and different locations, as a function of changes to precipitation.

5.3.2 Climate change and heritage policy in Scotland

In Scotland, the potential impacts of climate change on the historic environment have been recognised concurrently with elsewhere in the United Kingdom and Europe, associating natural phenomena intrinsically with wider issues involved in the sustainable management of the estate of properties in care.

The survival and condition of the historic environment is determined by natural processes, like climate change and erosion; and by human activities, such as land management, urban and rural development, transport and pollution. Its sustainable management is, consequently, related to the wider management of resources. Understanding the development of our environment through time helps inform decision-making about its management by offering a *longer-term perspective on important topics such as the nature and impact of past climate change and past management of the land, soil degradation and loss of woodland* (Historic Scotland, 2002, 11).

The *Scottish Historic Environment Policy* (SHEP) (Historic Scotland 2009, 2011) document highlights the need to include considerations of climate change as part of the sustainable management of the historic environment, emphasising the need for it to be acknowledged in all climate change mitigation policies and recommending that assessments of climatic impacts be conducted at susceptible locations. Further to this, the SHEP report emphasises the role to be played by historic properties in reducing emissions (Historic Scotland, 2009, 2011). Indeed, national targets for reductions to CO_2 emissions and the need for greater efficiency in the built environment provide an important consideration with regards to the interplay between the built heritage and climate change, with almost half a million buildings in Scotland dating to before 1919 (Rodwell, 2010). Given this stock, Historic Scotland is currently working to a *Climate Change Action Plan* for 2012-17, which seeks to support government objectives in terms of transitioning to a far less carbon-reliant economy (Historic Scotland, 2012). This document also confirms some of the primary threats to the historic environment in Scotland, highlighting rising sea levels and increased incidence of extreme rainfall events as foremost risk factors with cumulative subsequent effects in terms of wet-dry cycles, biological intrusion and the preservation of archaeological remains. Acknowledgement is also afforded within this to the possible consequences for traditional materials and rural dwellings, aspects of the built environment in which the earthen heritage is most prominent. This acknowledgement has not yet led to concerted efforts at extending the technical research base relating to Scotland's earth-built heritage, however, which this thesis seeks to address. Therefore, the controlled environment experiments described in Chapter 6 represent an attempt to integrate the conservation of Scotland's historic earth-built structures into a contemporary framework of heritage conservation research, based on inferences as to climate-related threats to historic earth building materials sought from a wide range of sources.

5.3.3 Climate-related threats to historic earth building materials

The World Heritage Earthen Architecture Programme (WHEAP) suggests that 34% of the 150 earthen heritage sites on the UNESCO World Heritage List are currently under threat from climate change (Joffroy, 2012). Specific reference to earth-built heritage is however limited in much of the policy literature alluded to above. Brimblecombe, for one, has acknowledged an under-appreciation of climatic impacts on vernacular and earthen building materials, although this relates to the Malian context (Brimblecombe, 2008). *The Atlas of Climate Change Impact* does emphasise the threats posed by extreme precipitation events to vernacular materials including cob and wattle and daub and also contains a section on the 'Decay of Clay Containing Materials', but this focuses on the likelihood for increased disintegration of clay containing sandstones in northern Europe due to increased precipitation and reduced frostiness in winters (Sabbioni *et al.*, 2010). Sabbioni *et al.* (2009) have noted the possibility of earthen materials drying out more rapidly in hotter summers. Warmer summers may superficially imply a reduced threat to the earthen heritage, but the annual or seasonal averages that are most widely referred to in climate science often hide a range of variables associated with the deterioration of materials on shorter temporal scales. This summarisation of the data hides an expectation for rainfall events to be more intense during summer periods, however, which would in turn lead to the possibility of short-term flooding and rapidly occurring wet-dry cycles (Brimblecombe and Grossi, 2007). English Heritage has acknowledged the potential for increased incidences of damage to historic cob buildings in England as a result of increased flooding (English Heritage, 2010) and Forster *et al.* (2008) have looked into the deteriorative effects of flood conditions on traditional cob walling. Recognition of the risks posed to earthen materials by climate change can also be found in documents produced by

ICOMOS, as a result of connections with ISCEAH, alongside recognition of vernacular architectures as 'energy… socially, culturally and ecologically efficient' (ICOMOS, 2008; 2009).

Fig. 5.3. Typical water-ingress issues stemming from inappropriate maintenance and site context problems. As noted, the deterioration of earthen building materials is most commonly related to damage from water ingress, a theme that punctuates the general earth building literature and which clearly has ramifications in relation to projected climate conditions.

Issues related to water ingress have long been identified as deleterious to insufficiently maintained or protected earth building materials, as testified in documents from the late-eighteenth century such as a request of one Marjory Campbell in Glenquaich stating that '…the Petitioner's Husband had in Summer 1780, built a large and commodious dwelling… using… mortar and clay instead of lyme… the wind and rain has now Quite melted away the said compound and has left the house in a ruinous condition…' (NAS GD112/11/2/3/85). Water ingress and associated impacts remain a primary concern to those interested in the conservation of Scotland's earth-built heritage. The projected climate changes related above highlight the likelihood of increased threats stemming from changes to seasonal precipitation patterns, increased incidence of extreme intra-seasonal precipitation and flooding events and corollary issues related to possible desiccation post-saturation or changes to freeze-thaw cycles. The mechanisms by which water may infiltrate or damage an earthen wall typically include capillary rise from the ground; submergence of the base of the wall in flood water; exposure of the head of the wall to rain as a result of thatch/roof deterioration; driven rain causing direct surface wetness and flow of water down the wall face; and, the trapping of naturally-occurring water vapour between the wall and impermeable cement renders.

Houben and Guillaud (1994) recognised the threat of flooding to earth-walled buildings, but related this specifically to the force of insurgent waves during events such as tsunami. Of greater concern in the United Kingdom, where mudwall structures are more commonly found inland in areas with poor drainage, is the increased incidence of submergence at the base of walls or extended periods of capillary rise from saturated ground and high water levels (Forster *et al.*, 2008). Medero *et al.* (2011) noted the fact that although water content is essential to the forces of cohesion that operate between clay particles within a mudwall structure, increased levels of saturation have a direct impact upon strength. They related this to increased incidences of flooding in recent times and the expectation that such events will exacerbate into the future. This insight informed flooding simulation experiments conducted in the laboratory that highlighted the critical role of straw in reinforcing mass earth walling material and underlined, through empirical observation, aspects such as the increased resistance to failure brought about by increased compaction and the occurrence of shrink and swell throughout the material when only part-submerged. The deterioration of mass earth walls as a consequence of water (containing salts) rising from the base is an issue that has been recognised by conservators since the 1960s (Carter and Pagliero, 1966). McIntosh (1974) noted the patterns of damage to historic mass earth walls in West Africa as a consequence of rain washing, rain splash and undercutting at the wall base and collapse after roof failure, as well as the movement of solutes from the interior to surface, with efflorescence leading to flaking following the evaporation of water. This is a point distributed more widely in Feilden's (2003) work on buildings' conservation. Brown, Robbins and Clifton (1979) were also able to associate the variable prevalence of soluble salts transported through capillary rise with the levels of deterioration exhibited in samples taken from the Tumacacori National Monument in Arizona. Nevertheless, the relative absence of scientific research pertaining to the mechanisms of deterioration in earth buildings leads one to seek insights from the long-established field of research related to the deterioration of building stone (Rainer, 2008). The movement of water through building materials is dependent upon factors such as porosity and material characteristics. Ordaz and Esbert (1985) suggested, for example, that Villamayor sandstone exhibits high capillary suction as a result of a high proportion of micropores, the presence of smectitic clays with high adsorptive qualities and a high degree of pore connectivity. High pore connectivity and the presence of micropores have also been attributed to increased incidence of salt damage in sandstones, with transportation in solution being followed by crystallisation (Ruedrich *et al.*, 2007). Feilden (2003) has discussed the general principles of capillary rise and salt transportation in porous media, noting that smaller pore size results in higher levels of water rise, which is in turn exacerbated by the simultaneous transportation of salts as increased salinity within walls provides a further attraction for groundwater with a lower level of salinity. As already inferred, salt efflorescence, crystallisation and hydration are widely recognised as key decay mechanisms in historic masonry structures, with the deterioration and flaking of stonework resulting from these processes at the surface (Houben and Guillaud, 1994). The recognition of climatic changes has stimulated reappraisals of such explanations (McCabe *et al.*, 2013), with Smith *et al.* (2011) having commented on notions of increased surface 'greening' and 'deep wetting' and the implications of these for salts-related decay of sandstone as a result of projected climate changes. They argue that prolonged periods of winter wetness will result in greater amounts of moisture at depth within building stone, with the corollary that soluble salts will penetrate correspondingly through ionic diffusion. Furthermore, wetting-drying cycles at the surface of materials, which can be as regular as intra-daily and have typically been the focus of sandstone decay research, will be lessened by the process of greening but with increased likelihood that salt reservoirs held at depth will contribute to surface decay when moisture leaches towards the surface from within.

Although climate projections indicate that freezing temperatures are likely to be less common in the future, increased winter precipitation and periods of seasonal extreme temperatures mean that freeze-thaw cycles will remain a threat to the integrity of mudwall structures into the future. External surface deterioration is associated with damp frost (Trotman, 1995) and subsequent thawing (Honeysett, 1995).I Ice expansion within the walls of buildings is critical to deterioration during colder periods, with contraction in the material being a product of thawing (Feilden, 2003). The presence of water is essential to the process of ice separation in soil microstructures, with the effects variable depending upon depth and the length of frost periods. Van Vliet-Lanoë, Coutard and Pissart (1984) investigated the changes to the structure of loamy soils as a consequence of repeated freezing and thawing, noting the particular susceptibility of such soils to these processes. Loams are typically used in earth building as they provide relatively even distributions of clay, silt and sand particles and can be sub-classified based on the relative predominance of any one of these (Chesworth, 2008). Using micromorphological descriptions of test (subject to a minimum of -7°C) and field (subject to a minimum of -17°C) soils, Van Vliet-Lanoë, Coutard and Pissart (1984) noted the development of unaccommodating platy structures as a consequence of ice segregation during freeze-thaw cycles (as opposed to the development of accommodating planes as a consequence of desiccation, although these can provide the basis for subsequent segregation). The authors demonstrated that such fissures are thinner towards the surface, becoming increasingly coarse at depth. Furthermore, they show that mammilated vesicles can develop in loams with clayish textures as a consequence of the eviction of air and structural collapse.

Some care must be taken when referring these processes directly to the deterioration of earthen walls, however, as certain actions may occur variably depending on the orientation of the material, with soil surfaces horizontal and walls vertical. Nevertheless, it is important to recognise that once formed, structural dissociations are permanent features within the soil materials of interest (other than in the event of biological activity) and therefore have implications for the integrity of earthen wall fabrics. Van Vliet-Lanoë (2010) recently updated this work, noting that frost actions such as ice segregation affect soils to a depth of up to 15 cm (Van Vliet-Lanoë, 2010, 81). If one considers the consequences of this in a 60 cm-thick vertical mud wall, potentially with two exposed faces, this suggests up to 25 or even 50% of material being subjected to forces of separation.

5.4 Using the UKCP09 Weather Generator to formulate climate projections for the Carse of Gowrie

The UKCP09 Weather Generator allows users to project future values for weather variables at locations more specific than those provided in the UKCP09 national and regional key findings discussed above. The underlying principles and applications of the tool have been detailed by Jones *et al.* (2009). The Weather Generator uses precipitation sequences to generate four primary variables, daily mean temperature, daily temperature range, vapour pressure and sunshine duration, which are then used to extrapolate variables such as daily minimum and maximum temperatures and relative humidity. Based on the same inputs as the climate projections available at 25 km^2 spatial resolution, the Weather Generator does not improve the reliability of projections but allows a valuable local data repository to be developed relevant to a specific area of interest at 5 km^2 spatial resolution and daily or hourly, rather than monthly or seasonal, temporal resolution. This in turn allows users to mine information such as the extents and relative likelihoods of extreme events for each period, a key aspect that is not provided by the summary 30-year projections available online.

The tool was thus used to project future climate for the Carse of Gowrie, where sampling of historic earth-built structures has been focused (Chapter 7), with a view to developing controlled environment studies based on inter and intra-seasonal daily cycles (Chapter 6). It was decided to generate the data as a 'worst case scenario' so as to give the starkest picture of potential differences from baseline conditions. The SRES A1F1 emissions scenario for the end of the twenty-first century at the 90% probability level was therefore used, meaning that the greatest range of outcomes could be considered. For both periods 100 separate files were generated, each containing a 30-year data sequence. This is deemed to be the minimum amount necessary for a robust scenario dataset (Jones *et al.*, 2009). For each period these files were amalgamated, giving two datasets that could be used to illustrate 30-year climate means as well as the relative likelihood of extreme weather variables.

Table 5.2. Summary table of baseline and future projected climate variables for the Carse of Gowrie, using the UKCP09 Weather Generator.

	Weather generator scenarios		
Projected climate variable	Baseline	2080s SRES A1F1	Projected change
Mean annual temperature, °C	8.1	11.9	+3.8
Mean daily minimum winter temperature (Dec-Feb), °C	0.1	2.8	+2.7
Mean daily maximum winter temperature (Dec-Feb), °C	6.0	9.0	+3.0
Mean daily minimum summer temperature (Jun-Aug), °C	9.3	13.7	+4.4
Mean daily maximum summer temperature (Jun-Aug), °C	18.2	23.3	+5.1
Mean daily precipitation, mm	2.0	2.1	+0.1
Mean daily winter precipitation (Dec-Feb), mm	2.1	2.8	+0.7
Mean daily summer precipitation (Jun-Aug), mm	1.9	1.5	-0.4
Mean annual relative humidity, %	83.0	81.0	-2.0
Mean winter relative humidity (Dec-Feb), %	87.0	87.0	0.0
Mean summer relative humidity (Jun-Aug), %	80.0	75.0	-5.0
Percentage days per annum with temperature <0°C	20.8	7.5	-13.3
Percentage days per annum with freeze-thaw cycles	19.4	7.4	-12.0
Percentage days per annum with precipitation >10mm	4.4	5.7	+1.3
Percentage days per annum with precipitation >20mm	0.7	1.2	+0.5

Comparison of the modelled baseline and projected data indicates that the general climate trends anticipated for the United Kingdom as a whole can be expected to be similar in the Carse of Gowrie. An increase in mean annual temperature of up to 3.8°C has the caveat of an increase in summer temperatures of up to 2°C more than for the winter, although the projected increase in mean minimum winter temperatures may be particularly significant in reducing the expected number of daily freeze-thaw cycles per year. Comparison of the percentage of days in each parent dataset where minimum temperature drops below 0°C and the maximum exceeds 0°C indicates a drop in the order of 12%, the equivalent of about 44 days each year.

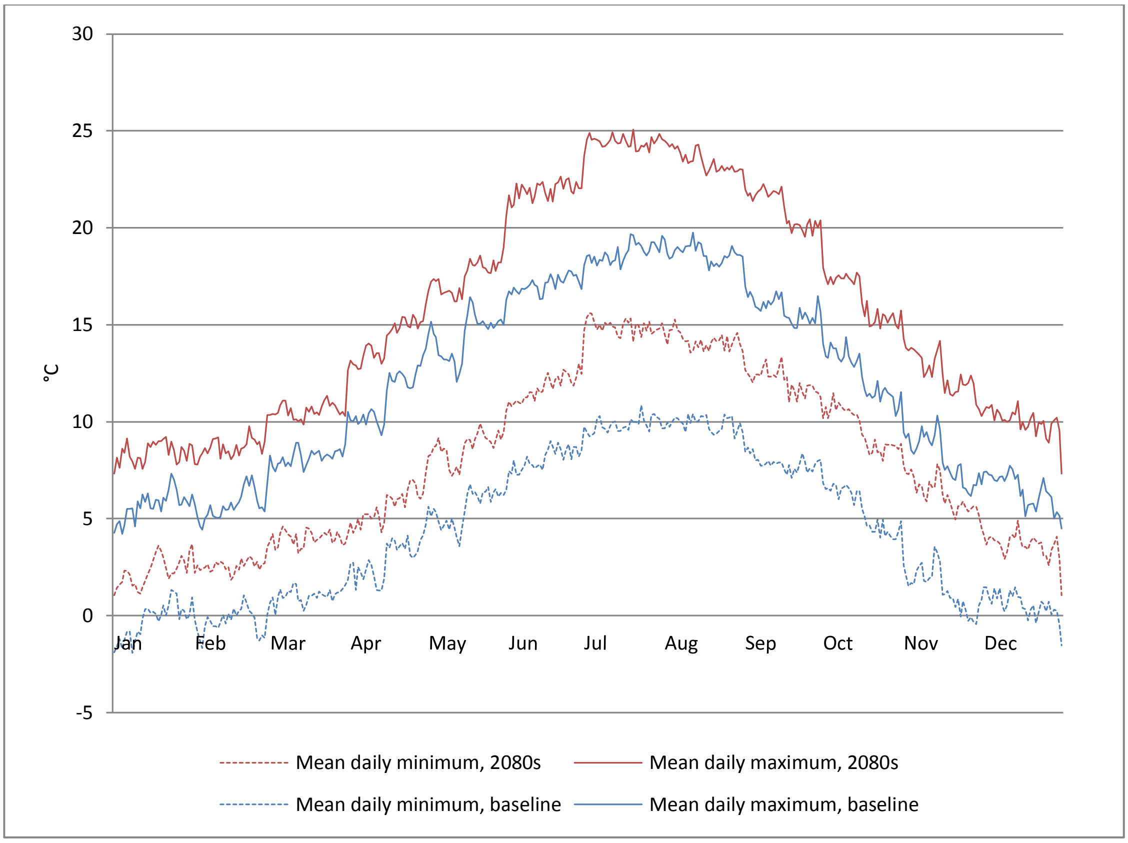


Fig. 5.4. Comparison of modelled baseline and future projected daily temperatures (“worst-case scenario”) for the Carse of Gowrie, using the UKCP09 Weather Generator.

The projected change in mean annual precipitation is negligible, but it is clear that seasonal shifts can be anticipated, with a projected increase of up to 0.7 mm per day in the winters of the 2080s and a decrease of 0.4 mm per day in the summers of the same period. This may mean an increased likelihood of winter flooding events followed by extended drier periods and therefore the exacerbation of swell-shrink cycles within earthen materials. Furthermore, it may also be that the behaviour of water within and around earth buildings becomes increasingly dynamic, with warmer winter temperatures and increased quantities of water around sites reducing the number of occasions where freezing temperatures may act as a block on movement, encouraging further infiltration and movement within walls.

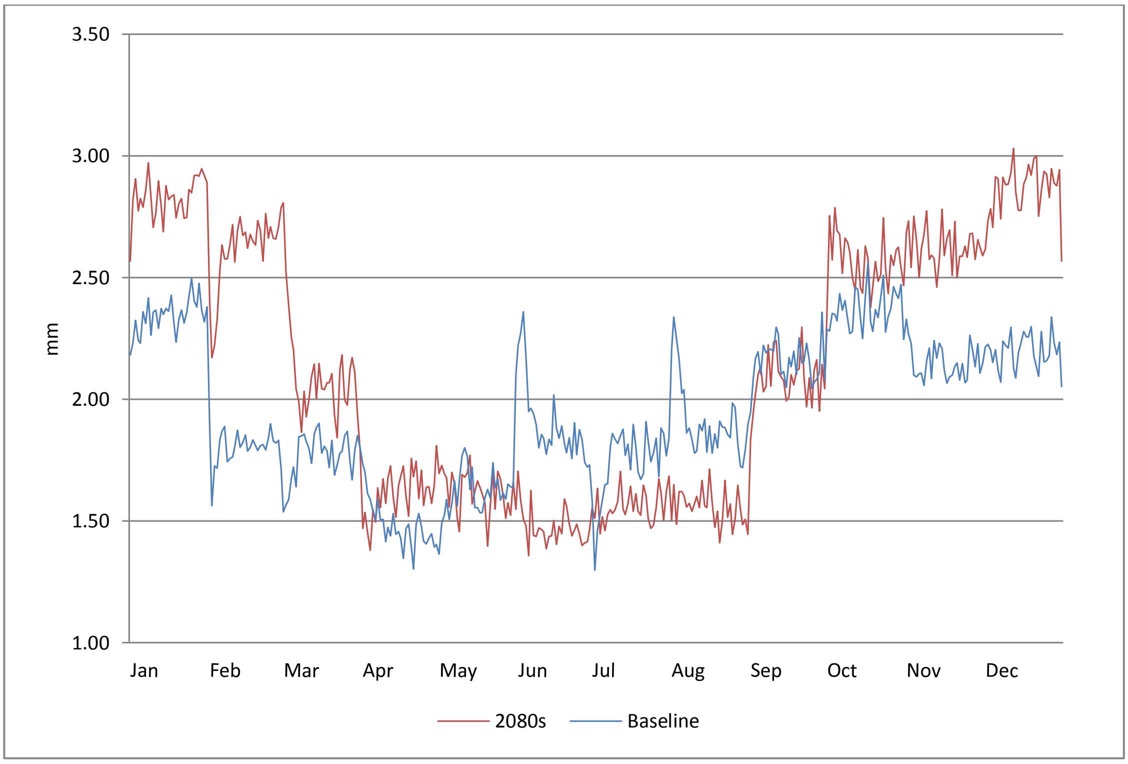


Fig. 5.5. Comparison of modelled baseline and future projected daily precipitation ("worst-case scenario") for the Carse of Gowrie, using the UKCP09 Weather Generator.

The projected changes to relative humidity show no change for the winter months but a decrease of 5% for the summer months. Interestingly, this would bring the summer mean relative humidity to 75%, which would suggest an increase in the incidence of NaCl crystallisation within materials as humidity oscillates around the critical figure of 75.3±0.5%. Furthermore, this change to summertime conditions would also increase the frequency of relative humidity oscillations around 71% (20°C), which Rodriguez-Navarro *et al.* (2000) have noted as being the point at which mirabilite ($Na_2SO_4 \cdot 10H_2O$) dehydrates to form thenardite (Na_2SO_4)$_{(and.)}$.

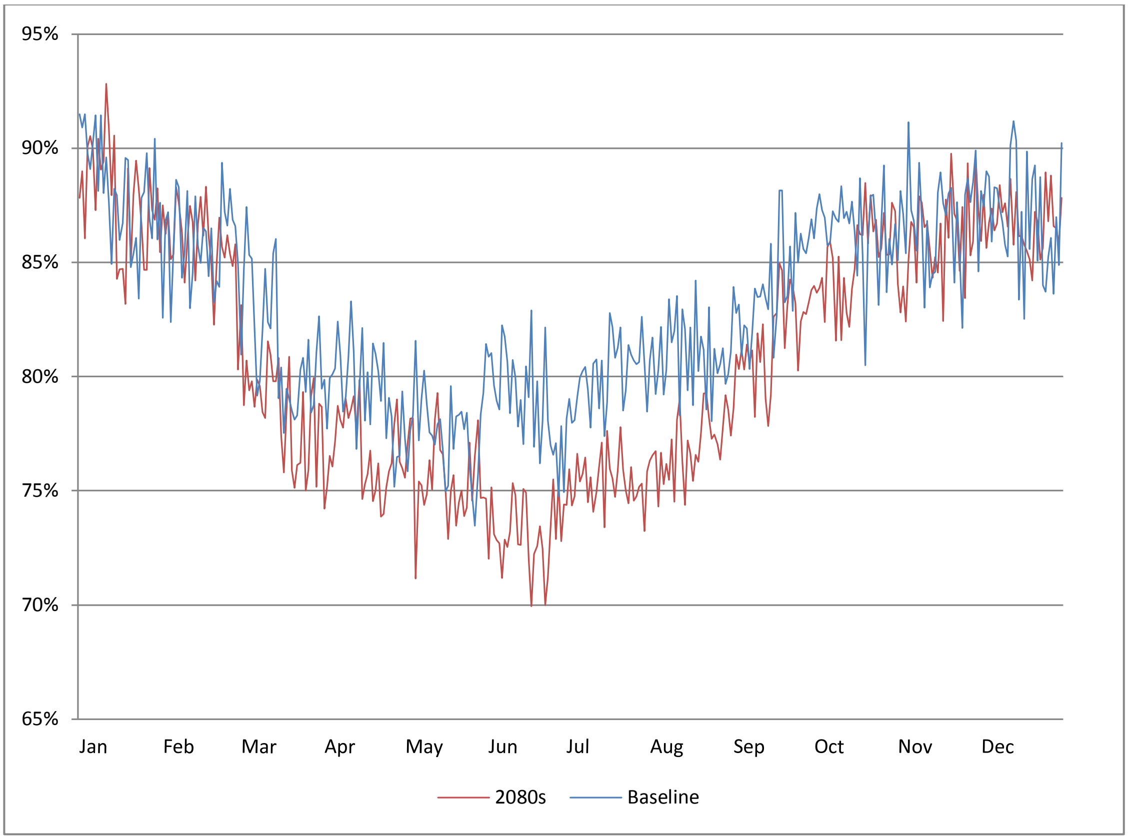


Fig. 5.6. Comparison of modelled baseline and future projected daily relative humidity ("worst-case scenario") for the Carse of Gowrie, using the UKCP09 Weather Generator.

5.5 Conclusion

Heritage policy formation is increasingly conditioned by the pressures of current and projected climate change. Consequently, efforts are required to be made in developing novel approaches to research that will inform strategies for the future management of the built heritage. The efforts made to address this have been considerable over the past fifteen or so years, augmented by a pre-existing research literature on environmentally-driven processes of deterioration, yet there remains an under-appreciation of earthen materials within this contemporary agenda. Using sources freely available to heritage practitioners, namely UKCP09 data and the Weather Generator tool, it has been shown here that relevant local climate projection models can be developed and used to infer potential risks to monuments and sites within a predetermined study area. This, together with the key drivers of mass earth deterioration identified through discussion of the relevant available literature, provides the basis for the climate cabinet experiments that are elucidated in the following pages.

6. Developing scenarios for controlled environment experimentation

6.1 Introduction

In order to complement the analysis of sampled materials and monitoring evidence gained from upstanding historic structures (Chapters 8-10), a series of controlled environment experiments were carried out to assess the performance and material characteristics of unfired earth blocks when exposed to climate scenarios developed using the UKCP09 Weather Generator. The results of subsequent analyses using micromorphological and micromorphometric techniques will be returned to in Chapter 10, with this chapter describing the rationale, objectives and process of experimentation.

6.2 Rationale for experimentation

Earth blocks were designed to be analogous in their material and structural characteristics with currently known mass earth mixes in Scotland, as described in earth building literature (Keefe, 2005, for example), in order that the results of experimentation could offer relevant outcomes. The blocks were subjected to a variety of treatments in climate cabinets (Snijders Scientific Microclima 1750E), which form part of the University of Stirling's Controlled Environment Facility.

These treatments were designed to provide comparative insights into the potential deterioration of mud walls in Scotland in relation to baseline and projected future climatic conditions. The treatments were designed to investigate factors deemed fundamental to the deterioration of mud walls, including the uptake of water through capillary rise and subsequent drying out of the material, repeated freeze-thaw cycles and soluble salt ingression. Clearly, the deterioration of earthen building materials is a complex area, with various interrelated, contributory and secondary aspects stemming from weather and climate phenomena, original structural design and continuing maintenance issues, such as biodeterioration and biological growth and intrusion, for example. The experiments outlined seek, however, to deal with a very specific set of criteria that, as already noted, are recognised as key drivers of mud wall deterioration.

Initial hypothesis:

- Earth blocks of varying composition, analogous with mass earth walls found within Scotland's built heritage, will suffer deterioration when subjected to different climatic factors related to water ingress. This deterioration can be observed at the macro-scale over the duration of the experiment and then analysed using micromorphological and micromorphometric analysis techniques subsequent to the experimental cycle.

Aim:

- The primary aim of the controlled environment experimentation is to consider the effects of different climatic regimes on the performance and deterioration of traditional mudwall materials.

Objectives:

The experiments were designed with the following objectives in mind:

- to test the performance of mudwall materials, at scales relevant to existing structures, when subjected to temperature and humidity cycles representative of baseline and projected climate conditions following the uptake of water or solute,
- to investigate comparatively the effects of projected changes to the winter-spring transition, which is here defined as the period from February to June, with winter saturation followed by an extended drying period,

- to assess comparatively the effects of projected changes to daily winter temperature oscillations, with particular interest in the effects of freeze-thaw cycles and frost and salt weathering; and,
- to engender relevant comparisons with materials extracted from extant structures in the Carse of Gowrie, using integrated micromorphological and micromorphometric analysis procedures and by following an analogously methodical approach to assessment based on a hierarchy of observational scales.

6.3 Block production

Clay was sourced from the now defunct Errol Brickworks, which is located around 1.5 km north-west of the village of Errol in the Carse of Gowrie, Perthshire. In order to replicate a range of mudwall mixes and the potential variability of clay content between regions, well-graded loose soil, gravel and organic barley straw were also acquired and used in combination with the Errol clay to produce a range of blocks with appropriate particle size distribution. An obstacle to achieving exact replication of materials found in upstanding survivals was that the block production and experimentation process was begun prior to any materials' assessment other than basic particle size analysis of samples of earth building materials taken from a variety of sites around Scotland. This was due mainly to constraints of time and climate cabinet availability. Particle size analysis revealed a great deal of variety in the clay : silt : sand ratios across the sites (Chapter 1, Table 1.1) and served to emphasise the futility of aspiring to replicate specific examples as this would fail to reflect the diversity that is encountered in the conservation of the earth built heritage. Of the five historic samples assessed at the time prior to block production, one was acquired from Logie Schoolhouse, in Angus, during the course of its restoration; two were taken from seventeenth century stone and clay-mortared townhouses in the town of Brechin, in Angus; one was removed from the gable end wall of the eighteenth century barn at Flatfield Steading, in Perthshire (Chapter 7; 3.3.1.2); and another was acquired from an organic-rich wall mortar acquired in Fladdabister, Shetland. Those samples from Logie and Flatfield were from mudwall structures of the kind most relevant to the experiments and, by extension, the greater extent of this thesis. The samples obtained in Brechin were of clay mortar and clay plaster, the former of which is mixed in much the same way as materials used in mudwall building. Similarly, the sample from Fladdabister was of earthen mortar material used to bind a stone-built wall. Perhaps most striking in the results is the great disparity between the make-up of the walls of Logie Schoolhouse and those at Flatfield barn, with these being based on the most similar methods of construction but located in geologically divergent locales.

It was decided to make four block types, using raw Errol clay soil, well-graded loose soil, <10 mm gravel acquired from a building merchant local to the University of Stirling and organic barley straw from Flatfield Steading. Four block types were manufactured, these being of 100% Errol clay; 25% Errol clay mixed with 66% well graded soil, 8% gravel and 1% straw; 20% Errol clay mixed with 71% well graded soil, 8% gravel and 1% straw; and, 15% Errol clay mixed with 76% well graded soil, 8% gravel and 1% straw.

Table 6.1. Quantities of raw materials used to make experimental blocks, 50 kg batches

Block type	Clay	Well graded soil	10 mm gravel	Straw
100% clay	50 kg	n/a	n/a	n/a
25% clay	12.5 kg	33 kg	4 kg	0.5 kg
20% clay	10 kg	35.5 kg	4 kg	0.5 kg
15% clay	7.5 kg	38 kg	4 kg	0.5 kg

The use of 100% Errol clay blocks provides a reference material from which to refer the performance of mixed composition blocks, also allowing specific inferences regarding the independent performance of the clay and silt-sized fraction. Dimensions of c. 220*105*133 mm were chosen for the blocks. This was deemed an appropriate size in order to maximise limited space within the climate cabinets, whilst ensuring that the blocks were large enough to withstand testing representative of real-world scenarios. This was an important consideration as it was essential that the blocks could be subsampled following treatment in order to manufacture thin sections for analysis using optical microscopy. The mixing procedure followed traditional mudwall building methods (Fig. 6.1), as found in historical accounts, with the earth component being mixed with aggregate, fibrous organic material and just enough water to give a malleable consistency. This was then trampled until the individual elements were all combined before being pressed by hand into a wooden mould, as is still done in the production of adobe bricks around the globe.

Fig. 6.1. Raw materials being mixed by foot in the traditional manner.

Although inexact, this production method provided a representative end product and quality control was maintained through the production of small batches of blocks using the same basic components in a single mould. Using this traditional wet method meant that the drying of the blocks had to be accelerated for the practical purpose of maximising use of the Controlled Environment Facility. This was done by holding them in the climate cabinets at 20°C and 40% relative humidity, until the weight of each block reached equilibrium. These settings were deemed to be appropriate so as to accelerate the drying process enough to allow for maximum use of the cabinets in experimentation, without acting too aggressively on the blocks and causing inadvertent damage prior to testing. Drying took around two weeks, although some variation was seen, corresponding to slight differences in the mass of the blocks, which were all 5 kg ±0.3 kg when fully dried. Inside the climate cabinets, the blocks were mounted on uniform sandstone plinths 4 cm thick, obtained from Historic Scotland, and held within plastic troughs that could be filled with water/solute. The sandstone plinths were chosen as they could be machine cut to a consistent size and provide a uniform porous medium through which water/solute could pass via capillary rise in a way representative of real-world scenarios.

6.4 Controlled environment experiments

Warke and Smith (2007) have suggested that it is important to develop experimental cycles resembling daily conditions in the real world in order to improve the likelihood of the resulting data being relevant to the built heritage itself. This approach is followed here. It should be noted that certain limitations were imposed on the experiments, including constraints on the capabilities of the climate cabinets, which provide a more than adequate temperature range of -20°C to 50°C but are only able to control relative humidity at temperatures over 5°C. More crucial, however, was the limit to the length of time allotted for accessing the climate cabinets. The following experimental cycles were programmed into the climate cabinets and required no manual intervention once started.

6.4.1 Experiment 1: Winter-spring transition

The "Winter-spring transition" experiment sought to explore the potential impacts of changes to the annual regime of accelerating temperature increase from winter to summer, concentrating on the period between February and June. The experiment was designed using eight blocks per climatic treatment, the plinths of four of each of these being submerged in distilled water at the beginning of the experimental cycle, with this being replenished weekly, and the remaining four being left dry.

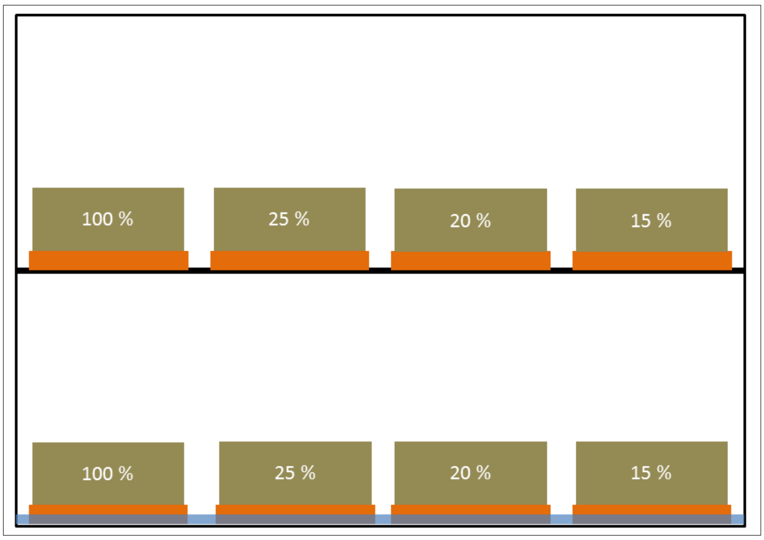


Fig. 6.2. Left: Experimental blocks being taken to the climate cabinet. Right: Schematic of block arrangement within the climate cabinets during the “winter-spring transition” experiments. Blocks were arranged from left to right based on percentage clay content, with dry samples held on the upper shelf and wet samples on the bottom with their plinths submerged in distilled water.

Using the weather generator data, the blocks were subject to daily cycles representing climate conditions for the months of February through to June. These ‘months’ were collapsed into six-day cycles, meaning that the experiments ran for a total of thirty days each.

Table 6.2. Winter-spring transition: baseline

	Mean daily RH	Step 1; 6hr	Step 2; 2hr	Step 3; 2hr	Step 4; 2hr	Step 5; 6 hr	Step 6; 2hr	Step 7; 2hr	Step 8; 2hr	Reps.
Feb' (day 32-61); 6 days	85.7	-0.29	Inc	2.75	Inc	5.79	Dec	2.75	Dec	5
Mar' (62-91); 6 days	81.3	1.09	Inc	4.66	Inc	8.23	Dec	4.66	Dec	5
April' (92-121); 6 days	79.5	2.92	Inc	7.12	Inc	11.32	Dec	7.12	Dec	5
May (122-151); 6 days	77.5	5.54	Inc	9.98	Inc	14.42	Dec	9.98	Dec	5
June (152-181); 6 days	79	8.04	Inc	12.55	Inc	17.06	Dec	12.55	Dec	5

Table 6.3. Winter-spring transition: 2080s										
	Mean daily RH	Step 1; 6hr	Step 2; 2hr	Step 3; 2hr	Step 4; 2hr	Step 5; 6 hr	Step 6; 2hr	Step 7; 2hr	Step 8; 2hr	Reps.
Feb' (day 32-61); 6 days	86	2.54	Inc	5.6	Inc	8.66	Dec	5.6	Dec	5
Mar' (62-91); 6 days	78	3.96	Inc	7.28	Inc	10.6	Dec	7.28	Dec	5
April' (92-121); 6 days	77	5.54	Inc	9.84	Inc	14.14	Dec	9.84	Dec	5
May (122-151); 6 days	76	8.59	Inc	12.99	Inc	17.39	Dec	12.99	Dec	5
June (152-181); 6 days	73	11.61	Inc	16.71	Inc	21.81	Dec	16.71	Dec	5

6.4.1.1 Macro-scale observations made during the experimental cycle

Baseline

Fig. 6.3. Observations of the earth blocks at weekly intervals (clockwise from top left) through the “Winter-spring baseline” experimental cycle indicated that water uptake was negligible in the 100 % clay block. All admixture blocks were saturated within two weeks of the start of the experiment. Although water uptake was prohibited in the 100 % clay block, there was a clear correlation between speed of water uptake and higher clay percentage in the admixture blocks.

2080s

Fig. 6.4. Observations of the earth blocks at weekly intervals (clockwise from top left) through the "Winter-spring 2080s" experimental cycle indicated the same pattern of water uptake as during the baseline conditions, but with reduced intensity. Higher clay content resulted in progressively increased uptake in the experimental blocks over the course of the experiment, whilst the 100 % clay block demonstrated limited water uptake within the first two weeks of the experiment before drying again towards the end of the cycle. It is worth noting the differential rates of water uptake when making comparisons between the two climatic regimes, particularly when considering the variable impacts of temperature on moisture within the walls of the Old Schoolhouse, Cottown, discussed in relation to microwave moisture sensor sampling in Chapter 8.

6.4.2 Experiment 2: Freeze-thaw cycles

Developing the first round of experiments, and following the principle of creating an actualistic experimental model, it was decided to add a weak sodium sulphate solution (0.01 M) to the troughs rather than distilled water, as this has been used by Historic Scotland in an experimental wall at South Gyle, Edinburgh, to replicate levels found in rainwater (Wilson, 2004). Furthermore, various authors have suggested that sodium sulphate of different phases is a cause of greater damage to porous building media than sodium chloride (Rodriguez-Navarro and Doehne, 1999; Rodriguez-Navarro *et al.*, 2000; Feilden, 2003). This solution was added at the start of the experimental cycles but not replenished thereafter as it was deemed important to avoid absolute block failure and thus ensure that subsamples could be removed for thin section production post-experimentation. It was also deemed important to create a more targeted pair of experiments, with a shorter running time and less variability within the experimental cycles. The cycles were, however, still run over successive twenty-four hour periods. The 0.01 M solution was prepared using anhydrous Na_2SO_4 (Ph. Eur. Grade Fluka 71963) following estimates for the concentrations found in garden soils in West Yorkshire (Wilson, 2004). The plinths of four of the blocks used for each climate were submerged at the beginning of the experimental cycle and the remaining four were left dry.

For the baseline conditions the blocks were subject to 9 hours at 3°C ('daytime') followed by 15 hours at -1°C ('night time'), with relative humidity nominally set at 80% when possible. For the future conditions the blocks were subject to 9 hours at 9°C followed by 15 hours at 3°C. The plinths of four blocks in each cabinet were submerged in 0.01 M Na_2SO_4 solution, with 2.5 litres used to fill each trough. The experiments each ran for 28 days.

Immediately following both sets of experiments, the earth blocks were processed and prepared for optical micromorphological and micromorphometric analyses in the University of Stirling thin section laboratory. Sub-samples were either taken by hand or cut from the blocks using a circular saw, depending on the extent to which the blocks were deteriorated before being dried using acetone exchange if necessary and resin impregnated. Thin sections were then manufactured using standardised methods (see page_232). The process of thin section production and methods and results of the subsequent analyses are elucidated in Chapter 10, being compared with evidence gained from the historic samples described in the following chapter.

6.4.2.1 Macro-scale observations made during the experimental cycle

Baseline

Fig. 6.5. By the end of the “Freeze-thaw baseline” experimental cycle the 100% clay block had completely failed and the admixture blocks exhibited surface damage whereby the outer material had dissociated and dried out.

2080s

Fig. 6.6. In contrast, all blocks retained their cohesion after being subjected to the “Freeze-thaw 2080s” experimental cycle and the lack of surface deterioration is indicated by the uniform retention of moisture across the admixture blocks.

6.5 Conclusion

This section has provided the bridging point of the thesis, whereby considerations of climate change and its implications for the built heritage links the historical appraisals used to emphasise the heritage value of Scotland's earth building traditions with scientific approaches to improving understandings of the performance and deterioration of surviving examples.

The experiments outlined were devised with a view to producing post-treatment materials comparable with those extracted during field sampling. The results of post-experimental analyses are elucidated after the discussion of fieldwork and analytical results pertaining to this. Nonetheless, some interesting observations were made during the experimental cycles, with the 100% Errol clay blocks showing hydrophobic behaviour in the "Winter-spring" experiments. Increasing amounts of the same material within the mixed composition blocks resulted in accelerated water uptake under both sets of conditions. Water uptake was increased in the blocks subjected to baseline conditions compared with those subjected to future projected conditions. Complete surface saturation of the mixed composition blocks occurred within two weeks under baseline conditions, whilst under future projected conditions complete saturation did not occur and the 15% clay treatment block exhibited particular resistance to water ingress. This may demonstrate that warmer conditions result in reduced water ingress and retention, which highlights the importance of habitation regimes as an integral part of ongoing maintenance as well as the importance of testing repair materials prior to use in order to determine their likely performance in relation to original material. For the "Freeze-thaw" experiments it is clear to see the effects of the more aggressive baseline treatments in relation to the future projected treatments, as well as those used in the "Winter-spring" experiments. The temperature regime was critical in causing the failure of the blocks subjected to baseline conditions and it is also interesting to note the extent to which surface deterioration occurred in these blocks compared with those subjected to the future projected conditions. It is tempting to assign this external damage to the effects of salt efflorescence, although such effects may have been inhibited by relative humidity levels, and the exacerbation of structural deterioration through ice lensing within the material.

The processing and micro-scale analyses of these experimental materials can be found in Chapter 10, but it is deemed important to first consider the evidence gained from work conducted in the field at sampling sites in the Carse of Gowrie. The following section therefore initially provides an account of the region and its earth buildings before providing specific details on the structures at which sampling has been conducted. Explanation of the sampling methods employed and subsequent analyses are then provided before returning to the assessment of experimental materials.

Sampling, analyses and results

7. The environment and earth-built heritage of the Carse of Gowrie and the introduction of field sites used for sampling

7.1 Introduction

The Carse of Gowrie is a low-lying tract of land, dominated by virgin estuarine deposits dating from the ice melt of the late Devonian (Peacock, 2003), which stretches at a breadth of between c. 3 km and 6.5 km for about 25 km along the north shore of the Firth of Tay between Perth and Dundee. This area is commonly regarded as having the most significant remaining concentration of earth buildings in Scotland, with particular attention paid to the village of Errol (Reen, 1999), and has provided most of the field samples referred to in this thesis.

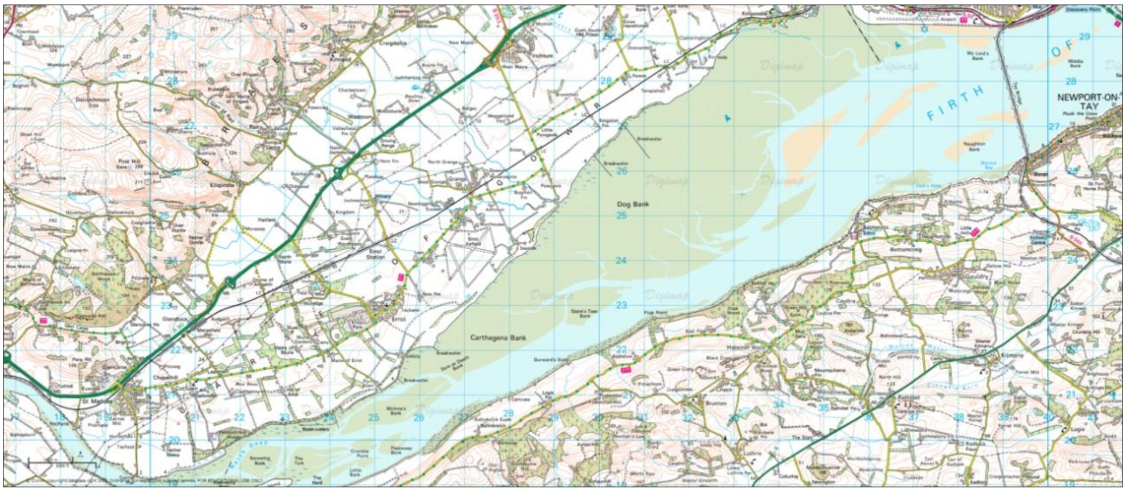


Fig. 7.1. The extremely flat topography of the Carse of Gowrie is highlighted in the Ordnance Survey 1:50,000 map for the area (accessed at http://digimap.edina.ac.uk/). This clearly holds implications for the drainage of the heavy clay soils.

7.2 The environment of the Carse of Gowrie

7.2.1 Clay soils

As noted already, an understanding of local environment is integral to understanding intrinsically associated vernacular building traditions. Leppard (1934) noted local reference to the clay-rich areas as ‘the true Carse’, comprising around 13,000 acres (c. 5300 hectares) of land beneath the 50ft (c. 15 m) contour adjacent to the Tay. The majority of the remainder (4000 from a total of 18,000 acres) is referred to by Leppard as the silt land, where the 'Inches' (once islands within the previously greater estuary, reflected in place names such as Inchmichael, Inchmartine and Inchture) are found above the clay-rich land. The entries for the parish of Errol in the *Statistical Account of Scotland* (Sinclair, 1791-99) and *New Statistical Account of Scotland* (Society for the Benefit of the Sons and Daughters of the Clergy, 1845) serve as useful points of reference in characterising the Carse. The *New Statistical Account* describes the lands of the Carse of Gowrie to the west of Errol as covered with deposits 'of gravel and red clay' reaching to depths of up to 60 feet, although incorrectly identified as alluvial, and to the east there is said to be found a 'pale blue clay, which continues for 20 or 30 feet' overlying peat. The "Old" account notes the 'excellent quality' of the soil, of which the low-lying majority is 'a strong clay'. It is stated that the parish lands are mostly 'ill adapted for pasture and too valuable to be left for that purpose' and the *Second Account* asserts that 'the flatter portions of the soil mak[e] up in richness and fertility what they want of the picturesque'. Such sentiments are echoed in later references to the Carse of Gowrie as the 'Garden of Scotland' (Leppard, 1934).

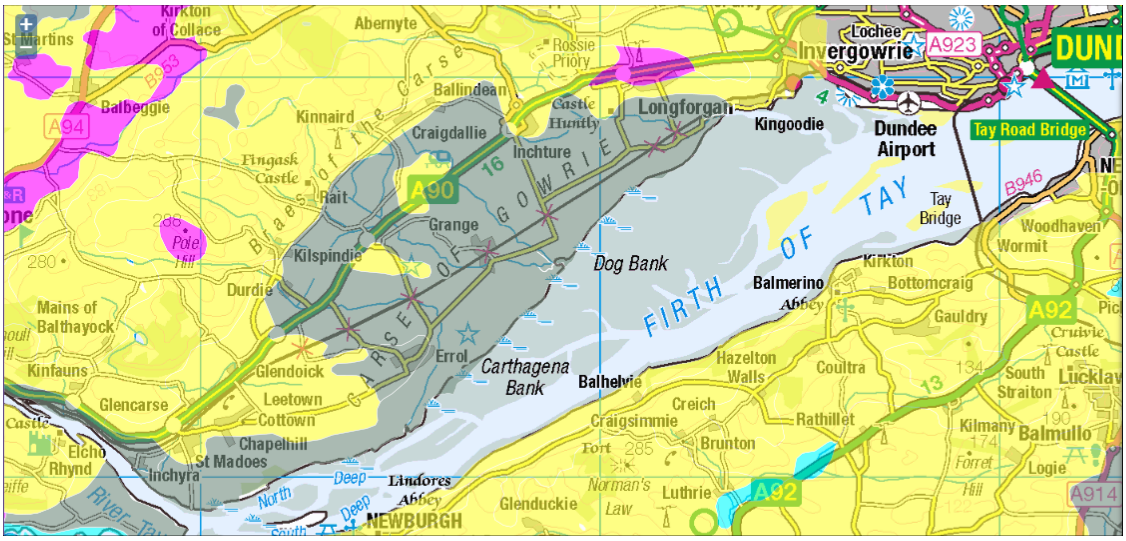


Fig. 7.2. The 1:250,000 Soil Map of Scotland indicates the predominance of Stirling Association noncalcareous gleys (grey) across the Carse of Gowrie. Accessed at http://www.soils-scotland.gov.uk/.

Modern landscape assessments have shown that the clay soils of the Carse are dominated by the Stirling Association (Soil Survey of Scotland; http://www.soils-scotland.gov.uk/), which has been noted for its silty nature (Morton and Winship, 2012) and is typified by interstratified illite-smectite, together with illite and kaolinite (Wilson *et al.*, 1984). Particle size analysis of the Errol clay used in experimental block production (Chapter 1; Table 1.1) confirmed that only 14.4% of particles were truly clay-sized (<2 µm), with 85.6% falling into the bracket of silt (2-63 µm), although the association is known to vary between 10 and 62% clay content with a mean of 31% (http://www.soils-scotland.gov.uk/data/soil-survey).

7.2.2 Weather

Historic weather records for the Carse of Gowrie can be compared with those of recent years to gain insights into the climate of the local area. Furthermore, setting these against modelled baseline conditions for the end of the twentieth century serves to demonstrate the consistency of the UKCP09 Weather Generator data and therefore its utility as a means of developing understandings of how climatic conditions may change over the course of the twenty-first century. Weather records for the Carse of Gowrie compiled over seven years prior to 1837 were entered into the *New Statistical Account* (Society for the Benefit of the Sons and Daughters of the Clergy, 1845) and provide a useful point of comparison with those provided a century later by Leppard (1934) reproduced below, which are based on a combination of data recorded at Perth and Dundee, as well as the Weather Generator data for the end of the twentieth century and recent records obtained from JHI Invergowrie, located at the eastern extreme of the Carse of Gowrie, covering 2011 and 2012. Rather than indicating the changing climatic patterns for the Carse of Gowrie, comparison of these datasets more usefully suggests the variations to be found around the reference point of the late-twentieth century, this being the only data set that exhibits climatic means representative of a thirty-year period.

Comparison of the mean monthly temperatures tabulated below suggests that the Carse of Gowrie experienced a particularly balmy period in the 1830s, with the warmest temperatures recorded for all of the months from May to October. The 1830s would also seem to have been warmer across the remainder of the year than in the 1930s and the late-twentieth century. The three most recent data sets exhibit very similar summer (May to October) temperatures, although the mean temperatures for the winter months (November to April) of 2011 and 2012 diverge notably from the rest. It should be noted that the data for the 1830s may be slightly misleading, however, as it is stated that temperatures were recorded once daily at 09:15, rather than being calculated as the mean of the diurnal temperatures for each day. Nonetheless, it may be suggested that these figures offer a reasonable approximation of mean daily temperatures from which to make general comparisons.

Mean monthly precipitation data for the 1930s and late-twentieth century follow very similar patterns, with the greatest differences seen in the data for July and August, which shows these months to have been particularly wet during the 1930s. In contrast, the data for 2011 and 2012 is both more extreme and more variable from month to month. This is reflected in the greater deviation around the mean monthly precipitation for 2011 and 2012 in relation to that recorded for the 1930s and representative of the late-twentieth century. These factors hint at the increasingly unpredictable conditions that have been projected for the remainder of the twenty-first century, with the possibility of increased incidences of extreme precipitation occurring throughout the seasons being of particular concern to the future of the Carse of Gowrie’s earth-built heritage.

Table 7.1. After Leppard (1934), with data converted from imperial to metric measurement values and columns inserted using data for Errol in the *New Statistical Account*, with temperature measurements having been taken at 09:15 over a seven year period prior to writing in 1837, and also using the UKCP09 Weather Generator data referred to in Chapter 5, together with observations made at the James Hutton Institute, Invergowrie.

	Reference Data					Leppard (1934)											
	Mean Temperature (°C)			Mean Precipitation (mm)		Temperature (°C)			Precipitation				Sunshine		Direction of Wind		
Month	Errol 1830s	Weather Generator baseline	2011-2012 JHI Invergowrie	Weather Generator baseline	2011-2012 JHI Invergowrie	Mean	Mean Max.	Mean Min.	Total (mm)	Per Cent of Annual	Days with Rain	Relative Humidity	Hours	Per Cent of Possible	Direction	Per Cent of Days	Days with Frost
Jan	2.7	2.7	3	72.6	48.2	2.8	5.6	0	55.8	7.6	16	88	44	24	SW	40	17
Feb	4.3	2.7	5	52.2	66.9	3.3	6.1	0	53.3	7.2	14	90	65	24	SW	29	16
Mar	5.6	4.7	7.5	54.7	33.0	4.4	7.8	1.1	58.4	7.9	16	82	100	28	SW	23	16
Apr	8.4	7.1	8.5	44.4	56.1	6.7	11.1	2.2	43.2	5.9	12	76	144	34	SW	21	12
May	12	10	10.2	50.5	71.3	10	14.4	5.6	53.3	7.2	14	75	167	33	SW	29	5
Jun	15.8	12.6	12.3	55.1	103.4	13.3	17.8	7.8	48.3	6.5	12	72	198	38	SW	30	1
Jul	16.7	14.3	14	54	103.7	14.4	18.9	10	71.1	9.7	15	78	170	32	SW	35	0
Aug	15.6	14.2	14.4	59.2	126.0	13.9	18.9	10	86.4	11.8	16	81	144	31	SW	39	0
Sep	12.7	11.8	12.5	64.6	49.5	12.2	16.7	7.8	53.3	7.2	14	82	124	33	SW	40	3
Oct	9.8	8.8	9.1	73.4	91.4	7.8	11.7	4.4	71.1	9.7	16	85	95	30	SW	38	9
Nov	5.1	4.7	7.3	66.7	51.7	5	7.8	2.2	68.6	9.3	16	88	63	26	SW	32	16
Dec	4.8	3.5	3.9	68.1	98.5	3.3	5.6	0	73.7	10	17	88	42	20	SW	37	20
Total				715.5	899.5				736.5	100	178		1356				115

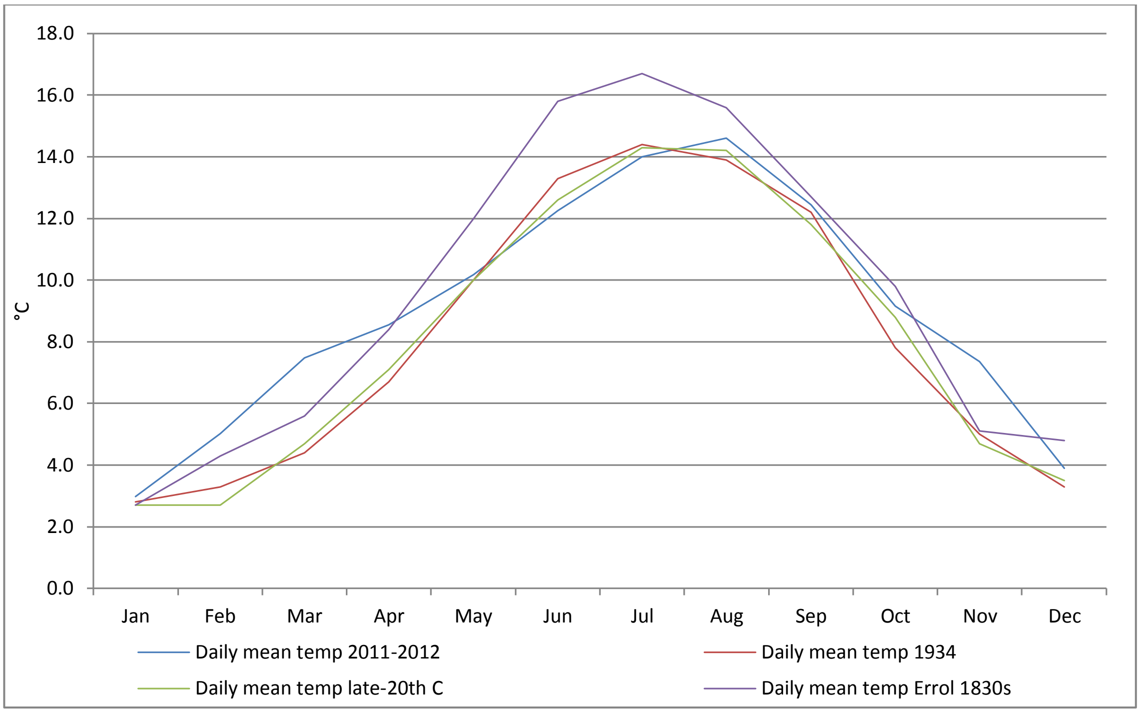


Fig. 7.3. Mean monthly temperatures in the Carse of Gowrie over time.

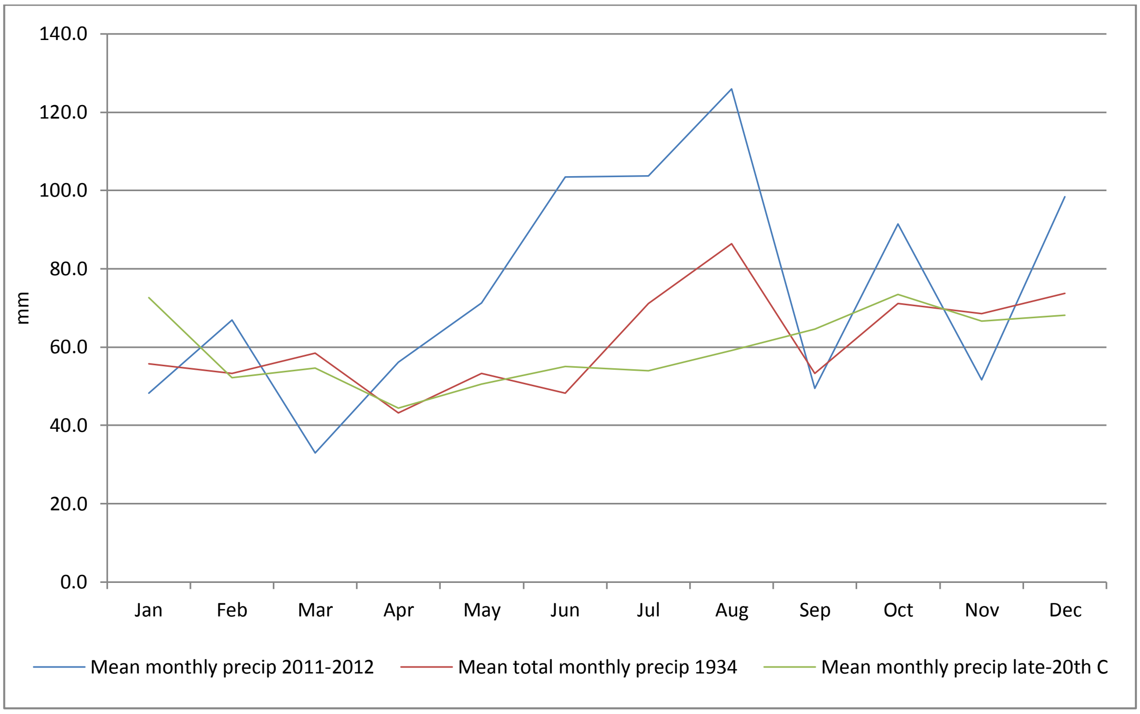


Fig. 7.4. Mean monthly precipitation levels in the Carse of Gowrie over time. Note the extreme data for the summer months of 2011-12 and variation across the autumn and winter months.

7.3 Earth buildings in the Carse of Gowrie

The prominence of the Carse of Gowrie's earth building traditions in comparison with others across much of the rest of Scotland has resulted in a relatively strong understanding of the nature and extent of earthen structures, based on those young enough to have survived for the benefit of those who have conducted modern surveys. The surveys by Walker and Fenton already alluded to have been built upon in specific relation to the Carse of Gowrie by White (2010) as part of a recent Master's thesis and through the efforts of the Tay Landscape Partnership (Morton and Winship, 2012). Historic landscape assessments recently undertaken as a preliminary stage of this project indicate the survival of 40 extant mudwall structures (only 5 of which have listed status), with 16 more 'possible' examples, as well as the identification of 65 lost and 5 'possible' lost examples. All of these recorded structures have been dated as being erected between 1745 and 1903, based on architectural understandings and local knowledge. As noted, Errol figures centrally in the Carse of Gowrie's earth-building traditions, with extant structures being identified along the high street, including numerous mudwall homes of two stories (Morton and Winship, 2012) that have unfortunately been cement rendered. The processes of agricultural improvement and urbanisation that took hold from the later-eighteenth century undoubtedly set in motion the chain of events that has ultimately meant the loss of extant mudwall structures, including all of those pre-dating the mid-eighteenth century, as well as a knowledge of materials and construction techniques that have been passed through countless generations prior to the twentieth century. The surviving examples that are known today therefore represent the vestiges of a medieval building tradition, the replacement of which was celebrated in the *General View of the Agriculture of the Carse of Gowrie* (Donaldson, 1794b):

'Previous to the year 1775, these [farm houses and offices] were in general but rudely constructed; the dwelling house, as well as the offices, being built of mud or clay, and the whole covered with straw. About that time, Lord Kinnaird having granted new leases over the greatest part of his estate, to substantial and intelligent farmers, and having also given them proper encouragement for erecting good houses, they soon afterwards built houses and offices upon regular plans, and the most substantial workmanship. The farm houses, over the whole district, are now in every respect commodious, substantial, and well set down. The dwelling house is of two stories, built of stone and lime, or brick covered with slate… The house in the different villages also, at the period mentioned above, very paltry and mean. Of late, however, several of the proprietors have expended very considerable sums, in erecting commodious and substantial houses for the inhabitants; and the villages of Errol, Balledgarno and Longforgan, in place of being a deformity, have now become an ornament to the country.'

Errol's location is described in the *Statistical Account* as 'remarkably pleasant', with an 'extensive and delightful' prospect. Its houses are said, however, to have been 'as paltry as the situation is pleasant. As there is no stone in the neighbourhood, they are mostly built of clay, and huddled together, without much order or regularity.' Nevertheless, it is admitted that all but those dwellings inhabited by the upper echelons of local society were of clay and that when this material was 'properly cemented' it was 'reckoned the warmest and most durable of any'. Interestingly, the account already notes the loss of local knowledge in erecting mudwalls, with such construction traditionally reliant on 'every man [being] his own mason', meaning that the newer structures lacked 'the solidity they had in past times' (Sinclair, 1791-99, **4**, 490). It is only these 'newer' structures that can be found today, however, thus demonstrating a durability that belies the suggestion in the "Old" account. As indicated by the Tay Landscape Partnership surveys, mudwalls continued to be erected through the nineteenth century in the Carse of Gowrie and a description of the building method from the Earl of Mansfield's factor, dated 1816, states the following:

‘I have made enquiries into the method of building clay cottages as practised in the Carse of Gowry… which is they first run up a sufficient quantity of clay on the most convenient spot for the intended house… then straw is strewed on the top of it and three or four horses are yoked together and they trample it until the straw is broke to pieces and properly incorporated with the clay… The clay is then fitt for use… the walls are then raised with this mixture about two feet in height and then left for about eight days (if dry weather) till it is set and then two feet more is added and so on till the walls are completed…’

This excerpt is taken from a series of correspondences that go on to indicate that the cost of erecting cottages in this way would amount to a minimum of £8/–, which was more than the cost of building on the same plans with stone (Walker *et al.*, 1996). This provides further evidence of the fact that mudwall dwellings, particularly in the Carse of Gowrie perhaps, were not an inherently inferior option to be taken out of financial necessity.

7.3.1 Earth buildings in the Carse of Gowrie used for sampling

Three buildings in the Carse of Gowrie provided monitoring evidence and samples that have been used as part of the research for this thesis. The Old Schoolhouse, located in the hamlet of Cottown, adjacent to the village of St Madoes, provides the main case study where all sampling and analysis techniques were employed following a hierarchical model. The two other sites of interest are the Flatfield Steading and the Leetown Victory Social Club, the latter of which was sampled as a derelict ruin and has since been completely lost.

7.3.1.1 The Old Schoolhouse, Cottown

Fig. 7.5. Water marks on the walls reflect the rise of water from the ground and during previous flooding events. Feilden (2003) suggests that the height of wetness at the surface of masonry walls reflects the levels to which critical water content has been reached internally.

The parish of St Madoes, roughly one square mile in shape and extent, is said in the *Statistical Account* to be dominated by 'deep strong' and 'adhesive' alluvial clays, which would seem, superficially at least, to indicate appropriate characteristics for mudwall building. Cottown had a population of 67 in 1839 (Society for the Benefit of the Sons and Daughters of the Clergy, 1845) and a later-nineteenth century photograph suggests that the inhabitants were predominantly housed in a line of structures similar to the Schoolhouse. This is corroborated by the commentary of Melville (1939), who noted the survival of a number of seventeenth and eighteenth century mudwall dwellings in Cottown in the 1930s and that the walls of some of these structures had been externally amended with bricks in the nineteenth century as a means of further protection from weathering. It may be that the decision to face the mudwalls with bricks was taken in order to deceive certain authorities who sought the replacement of the mudwall building stock (McGregor, pers. comm.).

Fig. 7.6. The Old Schoolhouse (right) and West Ruin (centre) photographed in the late-nineteenth century. Taken from *The Old Schoolhouse, Cottown: LHIS Feasibility Study* (NTS, 2011).

The single-storeyed Schoolhouse was originally built as a square-plan cottage in the mid-eighteenth century and its physical fabric has been altered and amended on numerous occasions. The mudwalls are built atop a low rubble plinth wall and were established to their full extent by the end of the eighteenth century when the building was extended to the east. Alterations thereafter were only made internally until a lean-to extension was added to the eastern end in the 1940s. The roof of the Schoolhouse, thatched with local Tay estuary reeds with a ridge of turf, is piended (hipped) at its younger, eastern end and the western wall is gabled. It is worth noting that gable walls are often the most vulnerable part of a mudwall building due to the complications involved in their erection (Harrison, 1999). Two ruinous structures of similar date to the Schoolhouse also occupy the site, one close to the western gable and the other lying on the northern boundary. A deep pond is located at the southern end of the Schoolhouse and the remnants of a historic orchard can also be found within the site boundary. An outdoor privy, brick pig sty and brick agricultural shed, all of mid-twentieth century date, complete the site (National Trust for Scotland, 2009). The designation of the Schoolhouse in 1992 as a Category A listed building, which reflects its national significance, was warranted on account of it being a rare example of a since lost vernacular tradition. Further to this, the building is deemed by its current owner, the National Trust for Scotland

(NTS), to be ‘remarkably complete’ having ‘evolved over time to meet the changing needs of a small agricultural community’.

Fig. 7.7. Architectural survey plans of Cottown Schoolhouse, provided by Stephen Copp.

The Schoolhouse fell into serious disrepair after becoming uninhabited in 1985 (Reen, 1999) and following its acquisition in 1993 by the NTS the building underwent a series of essential renovation and maintenance initiatives, with major works being concluded in 1997 and 2007. It was noted in 1995 that a ‘very gentle approach’ was taken during initial consolidation due to ‘the general lack of experience in dealing with this type of building’ (McGregor and Walker, 1995). An Options Appraisal for the Schoolhouse produced by the NTS Little Houses Improvement Scheme (LHIS) details a number of the remedies to problems encountered since 1993 (National Trust for Scotland, 2009), with many of the issues being common in historic massed earth buildings. Those relating to the initial repairs included ‘the removal of cement render, spot repairs to the mudwall, lime harling & limewashing, re-thatching of the roof in water reeds, the rebuilding of the south porch, and the installation of a perimeter drain.' It was noted at this time that the failure of the old thatch was permitting water ingress into the mudwalls from above, causing damage to some of the eastern wallheads. The Schoolhouse suffered extreme flooding during the 1980s (Reen, 1999) and winter flooding has become increasingly problematic at the site, with events in 2001 and 2002 leading to further repairs being made to the harling and thatch. Movement in the western gable wall prompted its stabilisation, with pre-dried cob blocks being used in isolated places to repair the base of the wall where submergence in floodwaters had caused undercutting and the loss of surface material (Forster *et al.*, 2008). During this period electric heaters were installed with the intention of encouraging an improved drying regime for the walls. Rat runs were also in filled at this time. Repeated repairs were also completed by 2007, bringing the structure back to a wind and watertight condition. Nevertheless, the Schoolhouse is still at risk as the site awaits further development and the necessary benefits of regular maintenance that come with occupation.

Fig. 7.8. Evidence of thatch deterioration, presumably as a result of bird activity. Such processes can have corollary implications in terms of water ingress.

Frequent flooding and associated water ingress from the ground are undoubtedly regarded as the greatest climate-related threats to the integrity of the mudwalls at the

Schoolhouse, although much of the evidence relevant to assessing the performance of the building in the face of climate-related impacts is conjectural or anecdotal. It has been suggested by local residents that the raising of the road that runs through the hamlet is related to increased incidences of localised flooding and a local newspaper report in February 2013 indicated a belief amongst the same group that blocked drainage ditches are the primary cause of flooding around the building, with this being contested by the NTS (Topping, 2013). It seems, however, that the physical context of the site provides the most tangible explanation to why the Schoolhouse suffers so acutely from flooding, with the building situated within the depression of a glacial drumlin. Notably, the western gable wall rests at the lowest point of this. Furthermore, a high water table encourages flooding and discourages drainage and it may also be that the pond overflows during flooding episodes. Episodic flooding events are inevitably followed by drying periods, which carries ramifications in terms of swelling being followed by shrinkage and cracking in the walls. As increased winter precipitation and warmer, dryer summers are predicted for the remainder of the twenty-first century, it seems that the long-term survival of the Schoolhouse (and its equivalents around Scotland and further afield) is partly dependent on improving understandings of the performance of the mudwalls during the annual period of winter-spring transition.


Fig. 7.9a (left). Internal flooding in the west room of the Schoolhouse, February 2011. Fig. 7.9b (right). July 2013: the impacts of repeated flooding are most prominently displayed at the internal side of the west gable wall, where repair blocks are being lost from the body of the mudwall.

Fig. 7.10. Flooding at Cottown Schoolhouse in early 2013. Note how the water gathers towards the western gable. Taken from http://www.thecourier.co.uk/news/local/perth-kinross/fears-for-historic-cottown-schoolhouse-1.68308).

7.3.1.2 Flatfield Steading

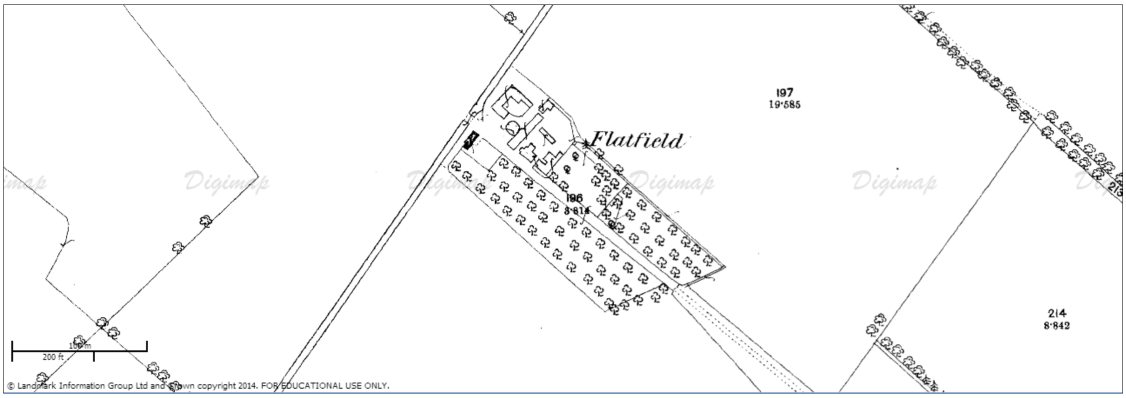


Fig. 7.11. Flatfield Steading as depicted by the Ordnance Survey in the 1860s, showing the mass earth outbuildings prior and the extent of the historic orchard. Accessed at (http://digimap.edina.ac.uk/ancientroam/historic).

The mixed farm at Flatfield, around 4 km north east of Cottown, was established in 1785 and has been in the possession of the family that now occupies it since 1825 (Walker and Walker, 1989). Part of the Errol parish, the site is comprised of the main farmhouse together with agricultural outbuildings laid out on a square plan. The main farmhouse is built with bricks apparently fired on-site in clamp kilns, whilst the older outbuildings were all erected with mass earth walls. A depression in the field to the south-east of the main house is said to denote the pit from where clay was procured for producing bricks for the house and building the single storey cart shed (now used as a cattery), the one-and-a-half storey storage shed and adjoining two-storey barn (see below). The techniques used in the construction of the mass earth walls are subject to debate, with the suggestion of Walker and Walker (1989) that the pisé method was used being undermined by the fact that fibre additives were included in the mix, as is typical of the mudwall method. The walls themselves are tapered to the top and devoid of tell-tale markings that would have been left by rammed earth shuttering (Whyte, 2010). The claywall method was certainly used for the parts of the two-storey barn that are faced with stone and it may be that temporary shuttering was used as a guide rather than formwork for ramming the un-faced walls. Like many historical mass earth buildings around the world, the barn and ancillary outbuilding closer to the main house at Flatfield were coated in cement render in the 1970s and the rate of deterioration that has occurred in the gable end of the barn within the last forty years is alarming. The gable itself – which was most recently comprised of brick, presumably as a replacement for original earthen material – is now completely lost, with the extant mudwall reaching eaves height. Furthermore, the barn was subject to even greater short-term risk when high winds ripped the roof from the structure in 2011, exposing the historic rafters and walls on two sides. The owners of the farm were proactive at this time, however, and secured the structural integrity of the barn for the foreseeable future by replacing the lost roof and using weather boards to protect the exposed wallheads at the gable end.

Fig. 7.12. During the 1970s cement render was applied to the exterior surfaces of all of the mass earth outbuildings with the ill-advised intention of protecting the mass earth walls. The numeric labels applied to the aerial photograph donate the following: 1. The farmhouse, dated 1785, built with bricks fired on-site in clamp kilns; 2. Detached mass earth outbuilding, originally one and-a-half stories and possibly used as a dwelling. The structure now functions as a cattery; 3. Mass earth storage shed/barn of one and-a-half stories, which has suffered a great deal of damage since the latter-part of the twentieth century. The structure has lost its western brick gable, which perhaps replaced a previously failed extension to the mass earth; 4. Stone-clad claywall extension of the storage shed/barn; 5. Stone-built byres now used as stables. (Image courtesy of Andrew Driver).

Fig. 7.13. The barn at Flatfield following the application of cement render in the 1970s. (Image taken from McCann, *Clay and Cob Buildings* [2004]).

Fig. 7.14.The cement render has failed and is gradually being shed from the walls of the barn and cattery. Although this seems to be taking place without causing excessive damage to the underlying fabric, the brick gable of the barn is now completely lost as a consequence of the deterioration caused. High winds in 2011 resulted in the loss of the corrugated iron roof from the barn and left it in a precarious state.

Fig. 7.15. Remedial works to the roof undertaken at the volition of the owners have since ensured the protection of the walls of the barn.

7.3.1.3 Leetown Victory Social Club

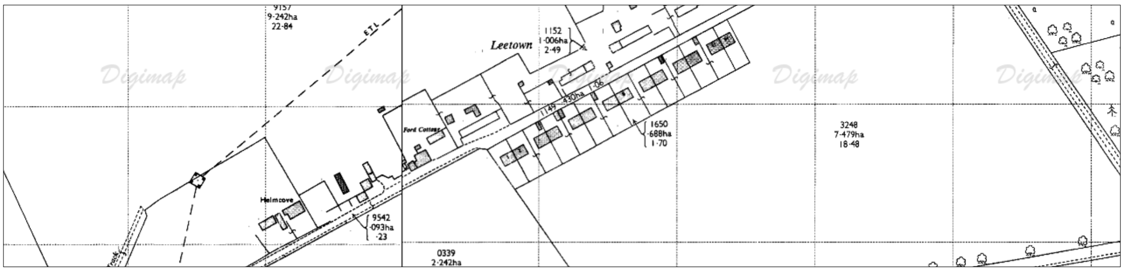


Fig. 7.16. Leetown as depicted by the Ordnance Survey in the 1970s, showing the Leetown Victory Social Club as the furthest structure on the left, set back from the road. Note that the structures on the south side of the road are a later-twentieth century development that replaced the vernacular dwellings that were originally aligned on the north side of the road.

Around 1.5 km to the east of Cottown is the small linear settlement of Leetown, which once comprised a line of mudwall dwellings that were replaced in the twentieth century by housing on the opposite side of the road running through the hamlet. The single vestige that remained of this older settlement, the Leetown Victory Social Club, was recorded by the RCAHMS in 1993 as a derelict unroofed structure, missing the majority of its north and west walls save for the area around chimney. This now lost structure was of unknown age but certainly more recent than the Cottown and Flatfield buildings, as the mud walls were faced with local bricks produced no earlier than the second quarter of the nineteenth century (White, 2010). The building was used by the local community until around 1960 (Whyte, 2010) but was abandoned after being deemed unsafe for use (McGregor, pers. comm.).

Fig. 7.17. The Leetown Victory Social Club photographed during survey by the RCAHMS in 1993, with red star donating the location from where material was sampled in January 2011. (© Crown Copyright: RCAHMS. Licensor www.rcahms.gov.uk).

A sample was taken from the mudwall material that surrounded the brick fireplace using a Kubiëna tin in January 2011, when the structure remained partly extant in a state remarkably similar to that recorded in 1993. Considering the level of dereliction witnessed by the earlier RCAHMS survey it is surprising that any earth component was still standing almost twenty years later and it may be that the permanent brick facing provided enough protection to prevent complete collapse. The structure has since been completely lost, however, save for a pile of brick rubble, which suggests that a point of threshold was reached in the process of deterioration in the mudwall material. It should be noted that this is the only sample known to have suffered from water ingression from all directions and thus provides an exemplar of fully deteriorated mudwall material.

Fig. 7.18. The site of the Leetown Victory Social Club photographed from the road in summer 2012, with little remaining evidence to suggest the previous presence of an earth-walled building.

7.4 Conclusion

The Carse of Gowrie presents a typical landscape context for mass earth buildings in Scotland and beyond, yet the region is also atypical in that it includes an extensive and, crucially, widely recognised suite of surviving earth buildings. This places it in contrast to areas such as the far south-west of Scotland, where the story of invisibility touched upon previously means that there are several enclaves of unrecorded earth structures, such as in and around the town of Stranraer (Adderley, Parkin and McLaughlin, submitted). The Old Schoolhouse, Cottown, provides the thesis with its primary case study, with the decision to focus upon a single structure being taken so as to allow for the fully integrated utilisation of all the investigative techniques available, with inferences from other samples and the experimental materials used to augment the results for the Schoolhouse. The structures at Flatfield and Leetown provide examples of how the earth building traditions of the region were extended in terms of technique and continued use of unfired earth into the nineteenth century.

8. Novel macro-scale approaches to monitoring and assessing earth-built heritage in the Carse of Gowrie

8.1 Field sampling methods

A hierarchical scale of sampling procedures was devised in the initial stages of the thesis, with the decision being taken to concentrate fieldwork as part of a case study of the Old Schoolhouse, Cottown. This allowed a full exploration of how complementary scientific techniques could be applied in conjunction to provide a holistic assessment of climate-related (particularly water ingress) impacts on a historic mudwall building that exhibits a variety of issues within a typical landscape context, although with myriad localised issues, and therefore offering wider resonance. This chapter concentrates on macro-scale sampling initiatives, being followed by the results of materials characterisations using X-ray methods and then by the results of micromorphological and micromorphometric analyses of extracted material samples. Complementary evidence was sought through the development of the experimental procedures explained previously, using the same micromorphological and micromorphometric approaches (Chapter 10).

8.2 Macro-scale investigations: temperature and humidity monitoring and microwave moisture sensor sampling

The monitoring of temperature and humidity within the walls of the Schoolhouse and the Flatfield Barn and the programme of measuring relative moisture content within the walls of the Schoolhouse provided the opportunity for macro-scale insights into the performance of mudwall structures in relation to weather-related stresses in the real world. As such, these monitoring and sampling initiatives must be contextualised with records of local weather throughout the relevant periods of time in which they took place.

8.2.1 External weather conditions

Regional monthly weather data were obtained from the James Hutton Institute, Invergowrie, for the period from January 2011 up to April 2013 (Table 8.1). These data provide a reference for conditions in the area throughout the time that temperature and humidity monitoring within the walls of the Schoolhouse and Flatfield barn took place and for when microwave moisture sensor (MMS) sampling was conducted at the Schoolhouse (8.2.2. and 8.2.3., respectively).

Mean daily minimum and maximum temperatures and mean daily precipitation levels are provided here for each month together with total monthly precipitation and determinations of the number of frost and wet days, following the example of Sabbioni *et al.* (2010).

Table 8.1. Monthly weather observations at the James Hutton Institute, Invergowrie, Dundee, January 2011-April 2013. Data relating to the period during which sampling was conducted is in bold.

Month	Air Max °C	Air Min °C	Daily mean temp °C	No frost days	Daily mean rain mm	Total rain, mm	No wet days (>1 mm)
Jan-11	5.7	-0.9	2.4	18	2.3	63.6	10
Feb-11	7.7	1.7	4.7	3	4.2	112.2	20
Mar-11	10	1.9	5.95	7	2.2	60.6	8
Apr-11	15.4	5.6	10.5	0	0.4	9.8	2
May-11	15.1	6.2	10.65	1	3	77.2	12
Jun-11	17.4	8.4	12.9	0	2.4	65.4	14
Jul-11	18.5	10.1	14.3	0	3.9	105.4	10
Aug-11	17.7	10.3	14	0	4.8	125.7	12
Sep-11	17.1	9.9	13.5	0	2.1	57.1	13
Oct-11	13.6	7.4	10.5	0	3.1	75.5	12
Nov-11	12	6	9	2	2.3	57.9	13
Dec-11	7.9	0.9	4.4	10	1.9	54.3	10
Jan-12	7.1	0	3.55	12	1.1	32.8	7
Feb-12	8.5	2.2	5.35	8	0.8	21.5	4
Mar-12	**14**	**4**	**9**	**4**	**0.2**	**5.3**	**2**
Apr-12	**10.3**	**2.9**	**6.6**	**6**	**3.4**	**102.4**	**15**
May-12	**13.8**	**5.6**	**9.7**	**0**	**2.1**	**65.4**	**11**
Jun-12	**14.7**	**8.6**	**11.6**	**0**	**4.7**	**141.4**	**14**
Jul-12	**17.1**	**10.3**	**13.7**	**0**	**3.3**	**102**	**14**
Aug-12	**19.4**	**11**	**15.2**	**0**	**4.1**	**126.2**	**14**
Sep-12	**16.1**	**6.8**	**11.4**	**0**	**1.4**	**41.9**	**8**
Oct-12	**11.7**	**3.8**	**7.8**	**4**	**3.5**	**107.3**	**13**

Nov-12	**9**	**2.3**	**5.7**	**9**	**1.5**	**45.5**	**10**
Dec-12	**6.2**	**0.7**	**3.4**	**6**	**4.6**	**142.6**	**14**
Jan-13	**5.8**	**1.2**	**3.5**	**12**	**3.2**	**100**	**16**
Feb-13	**6.3**	**0.3**	**3.3**	**13**	**1.2**	**34.3**	**3**
Mar-13	**5.1**	**-0.1**	**2.5**	**17**	**2.2**	**67.6**	**13**
Apr-13	**10.7**	**2.2**	**6.5**	**6**	**1.2**	**36.5**	**8**

The fourteen month period within which monitoring activities were conducted was one of great extremes, more or less bookended by an abnormally warm March 2012 and abnormally cold March 2013. The latter of these saw the lowest mean temperatures for the whole period and therefore the prolongation of winter conditions. The number of days per month in which temperatures of 0°C or less were recorded reflects this further. Most relevant to the assessment of water uptake at Cottown, however, are the records for precipitation. Seven out of ten months between April 2012 and January 2013 experienced total rainfall of over 100 mm with a mean of 14.3 wet days across these. June, July and August 2012 each had 14 wet days, with mean monthly precipitation across this period of 123.2 mm. No flooding was recorded at the site over this period, however. October 2012 saw the fourth highest monthly precipitation of the thirteen month period, being followed by a November with the fifth lowest total monthly rainfall. December 2012 was the wettest month, with 14 wet days and 142.6 mm of rain falling. 242.6 mm of rain fell over the course of December 2012 and January 2013, with 30 wet days recorded across these two months. February 2013 experienced the second lowest total rainfall and only 3 wet days and in March 2013 61.8 mm of rain fell before the 20th. April 2013 was the third driest month, with 36.5 mm total rainfall and the average monthly precipitation for February, March and April 2013 was 46.1 mm. The effects of freeze-thaw are of primary concern to the conservation of historic buildings such as the Schoolhouse and the extreme cold experienced from January to March 2013, coupled with flooding, might have caused significant damage. Although the winter-spring of 2012-2013 may not be representative of future projected conditions (fewer winter freezing events), it may reflect the increasing regularity of extreme events, thus making it a useful case study.

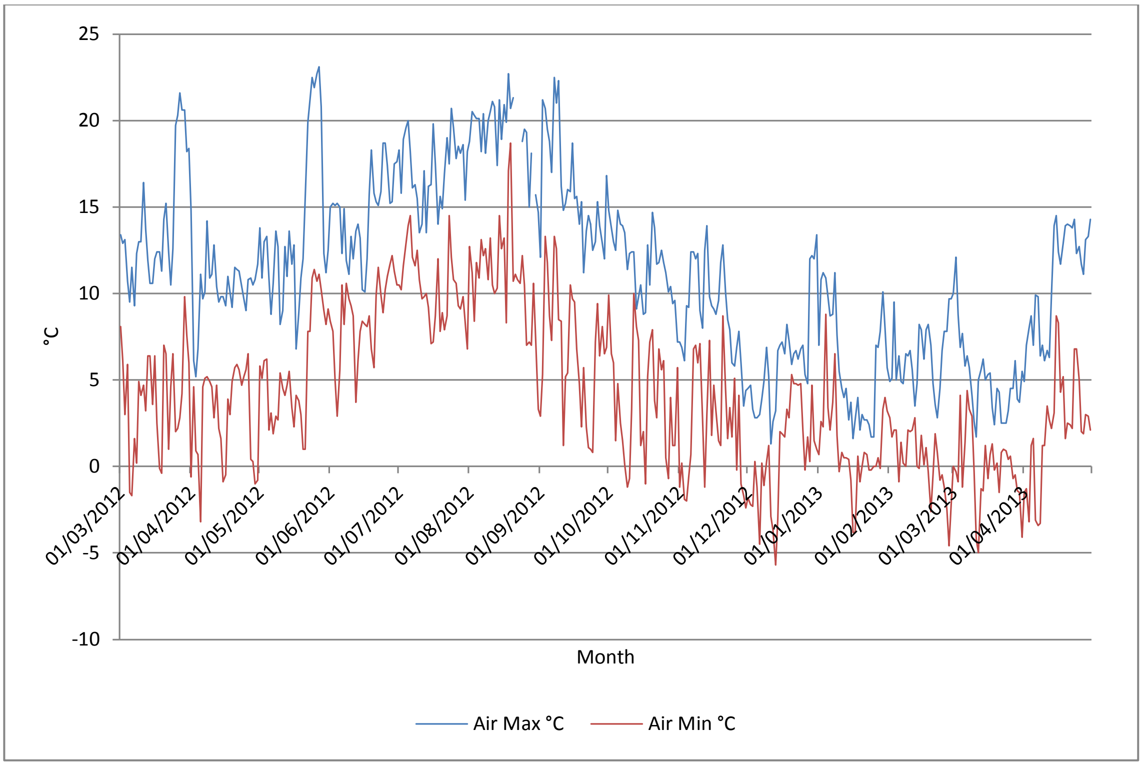


Fig. 8.1. Daily minimum and maximum temperature recorded at JHI Invergowrie, March 2012 to April 2013.

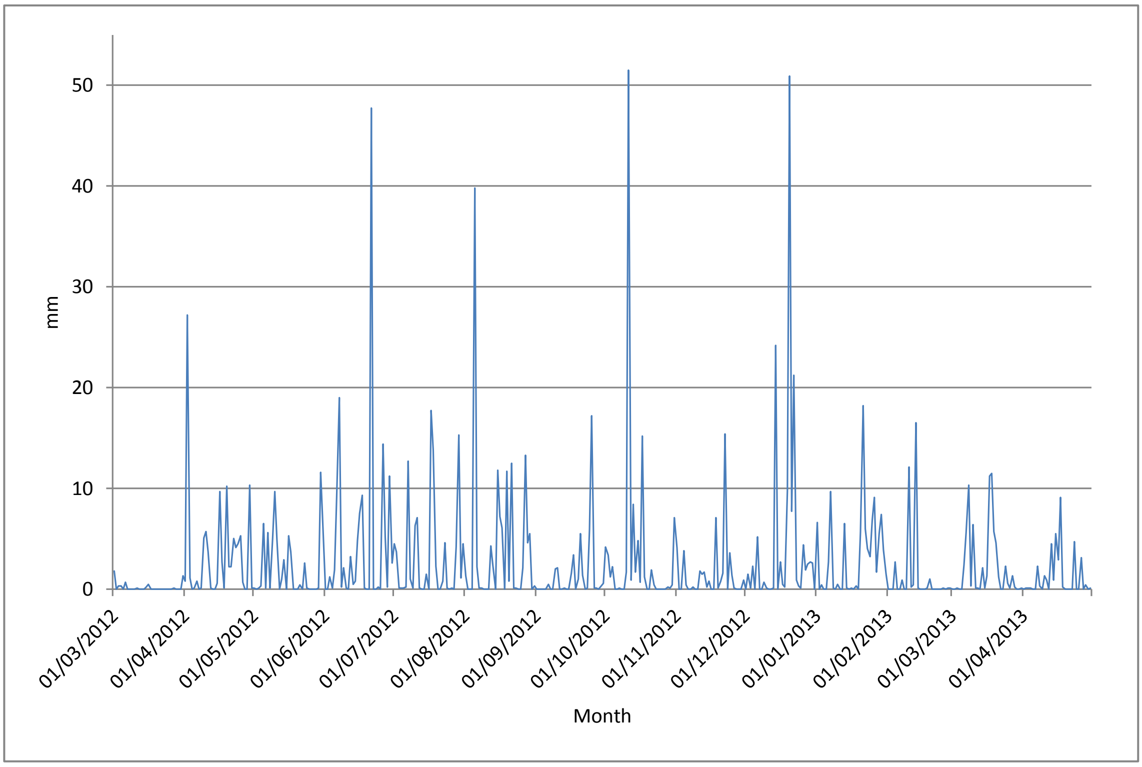


Fig. 8.2. Daily precipitation recorded at JHI Invergowrie, March 2012 to April 2013.

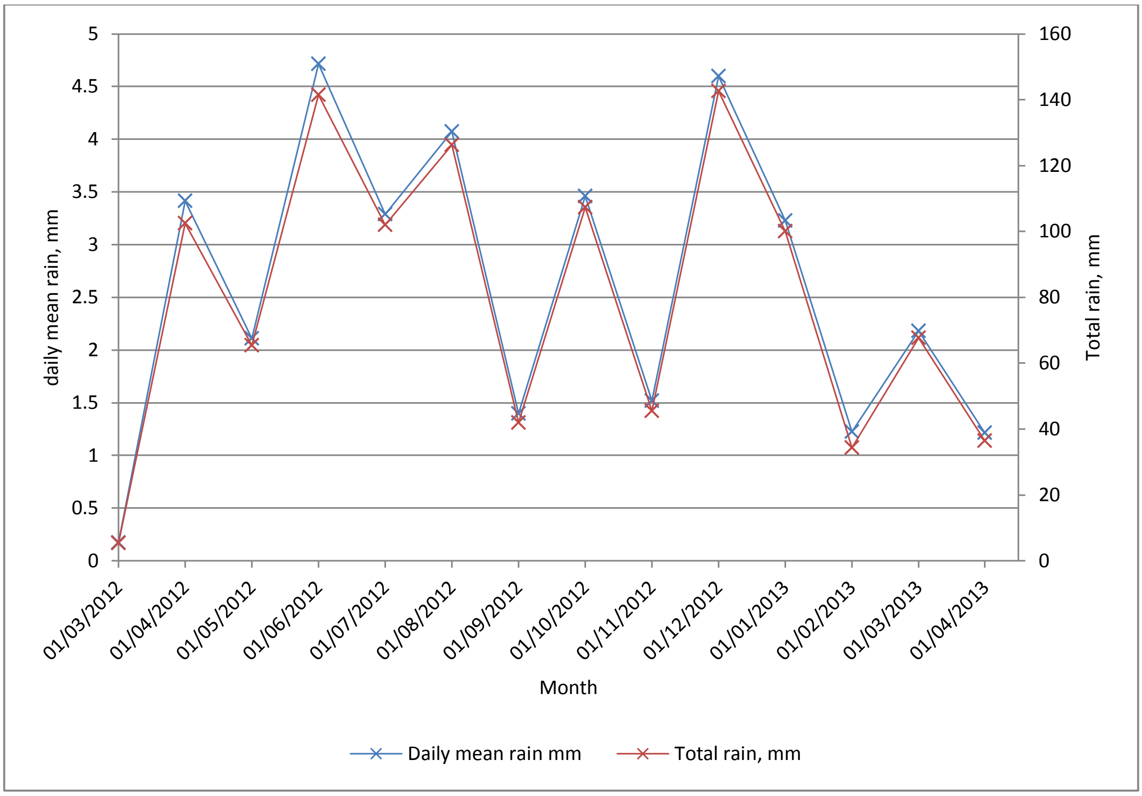


Fig. 8.3. Mean daily and total precipitation by month recorded at JHI Invergowrie, March 2012 to April 2013.

8.2.2 Temperature and humidity probe data

Temperature and humidity probe monitoring data for the Old Schoolhouse were obtained through links developed with Arc Architects and University College London (UCL) as a result of shared interest in the building. It was determined that it would be prudent, following the protocol of minimal intervention integral to conservation philosophy, to gain access to the data gathered by Arc/UCL rather than to re-instrument the walls of the building. Data were acquired from standalone probes (EL-USB-2-LCD- EasyLog temperature and humidity USB, Lascar Electronics, UK) that were in place at three heights within the west gable wall of the Schoolhouse as of January 2012, recording temperature and humidity twice per hour per day. These probes are 125 mm in length and have a diameter of 20 mm, with the latter measurement key to ensuring minimal intervention into the wall. The first two probes were located at 0.3 m, with the third at 1 m. The probes were relocated on April 26, however, to heights of 1.2 m and 1.7 m from the ground and 0.5 m above the eaves (page 192).

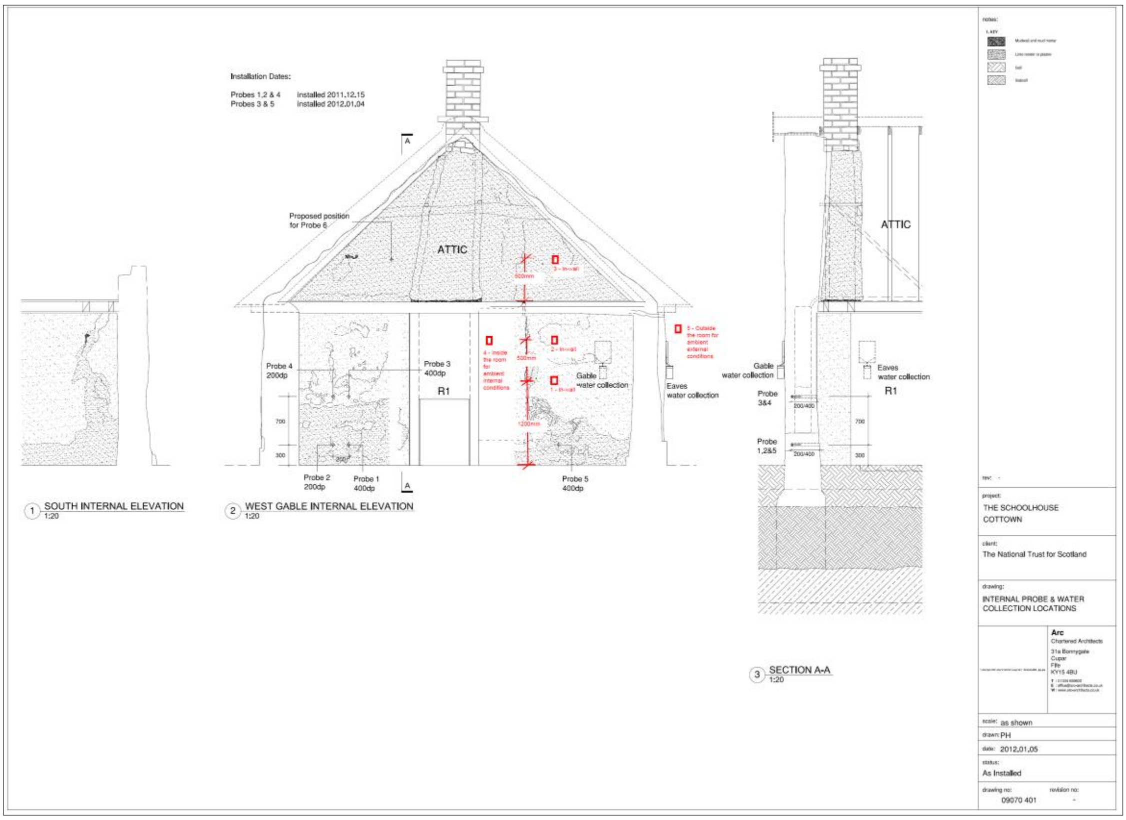


Fig. 8.4. The locations of Easylog temperature and relative humidity probes in the west gable at Cottown Schoolhouse.

To complement the Schoolhouse data, and to provide a point of comparison with this, the corner of the north and west walls of the barn at Flatfield was instrumented with “iButton” integrated sensor and data loggers (DS1923 Hygrochron iButton; Maxim Integrated Corp., San Jose, USA), with the locations being suggested and approved by the owners. iButtons were identified as a particularly appropriate means of internally instrumenting mass earth walls with minimal intrusion due to their small size (17.35 mm diameter*5.89 mm depth). It was known that they have been used with success in unpublished experimental studies conducted by Historic Scotland at South Gyle, Edinburgh, which sought to investigate the effects of solute uptake in experimental masonry walls. The iButtons were held within muslin cloth and inserted at a depth of ~20 cm into the wall, with the hole backfilled with locally sourced clay from the disused Errol brickworks. One iButton was located at a height of ~50 cm above ground level in the western end of the north wall and the other was located centrally within the west wall at first-floor level. Measurements were recorded by both probes daily at 01:00 and 13:00.

Table 8.2. Summary table of temperature and relative humidity data recorded from within the mass earth walls at Cottown and Flatfield.

	Old Schoolhouse, Cottown						Flatfield Steading Barn			
	1		2		3		50 cm		First floor	
	°C	% RH	°C	% RH	°C	% RH	°C	% RH	°C	% RH
Mean	8.0	94.5	8.2	95.3	8.6	93.3	8.2	89.5	9.1	85.2
Standard deviation	4.6	2.8	4.6	2.7	4.8	0.8	4.3	1.7	4.9	2.3
Min	-1.0	68.0	-1.0	68.0	-0.5	89.0	0.5	84.3	-2.0	81.4
Max	17.0	100.0	18.0	100.0	18.5	97.0	17.1	93.4	20.6	90.1
Range	18.0	32.0	19.0	32.0	19.0	8.0	16.5	9.1	22.6	8.7

The relative temperatures exhibited for the gable wall of the Schoolhouse remained consistent between each probe, with slightly higher temperatures observed at greater height reflecting a difference in mean temperature between the lowest and highest probes of 0.6°C. The diurnal temperature data obtained from the walls at Flatfield also revealed differences depending on the height at which the iButtons were located within the wall, with the difference in overall means being 0.9°C. Between November and February, however, the difference in mean temperature between the two iButtons was reduced. Daily temperature changes within the gable wall of the Schoolhouse tended to be delayed in relation to external temperatures, rising from late-morning or afternoon and being maintained until late at night before falling over the course of the early morning hours. The range in temperatures recorded at Cottown was 18°C at the lowest level and 19°C at the two higher levels. Night-time temperature within the wall at Flatfield was warmer on average by 0.5°C at first-floor level and by 0.2°C at 50 cm. The higher iButton also recorded greater variation in temperature over the course of time and retained heat through the night, with a maximum of 20.6°C (28/05/2012, 01:00) versus 17.1°C at 50 cm (19/08/2012, 01:00). This emphasises the thermal performance of mass earth walls, which clearly retain heat absorbed during the daytime well into the night. It should also be noted that although external temperature frequently dropped to well below 0°C during the data collection period, the temperature recorded within the walls at both sites stayed above freezing throughout, with the of exception 13-15/12/2012. This is perhaps key to explaining the resilience of the Schoolhouse. The minimum external temperature for the entire period was recorded on 13/12/2012, occurring within a four-day spell where minimum temperatures were consecutively -2.9°C, -3°C -5.7°C and -3°C. The lowest probe at Cottown recorded a temperature of -0.5°C at 00:13 on 13/12/2012, with the mid-level probe recording a fall below freezing over four hours later. The highest probe followed suit by 14:43 the following afternoon, staying at 0.5°C until the next evening. The lower probes fell to -1°C with the same rate of lag and maintained this temperature over the course of the day before rising over the early evening (mid-level) and night-time (lower level) of 14/12/2012. Conversely, the minimum temperature at Flatfield of -2°C (13/12/2012, 13:00) was recorded at first-floor height, whilst that at 50 cm from ground level never went below 0.5°C (13-14/12/2012). This may be explained as slightly anomalous due to the brick storage structure that is appended to the exterior of the wall at this point, although the disparity may have also been influenced by the exposure of the upper level of the wall as it is not tied into the roof system. Overall mean temperatures increase with height in both structures, with the implication that greater levels of wetness within the material at the bottom part of each wall equates to lower temperatures within the walls. This notion of increased wetness is not necessarily reflected in the relative humidity values for Cottown, but is demonstrated through MMS sampling (8.2.3.).

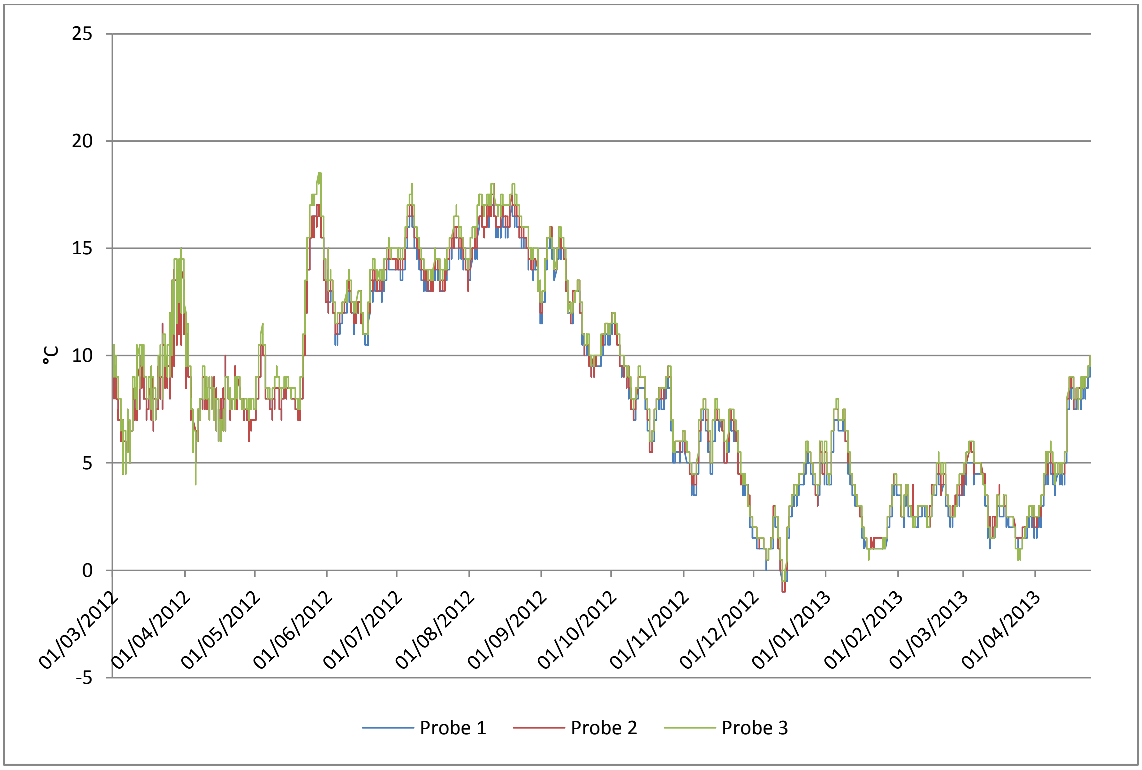


Fig. 8.5. Temperatures recorded within the west gable wall of Cottown Schoolhouse.

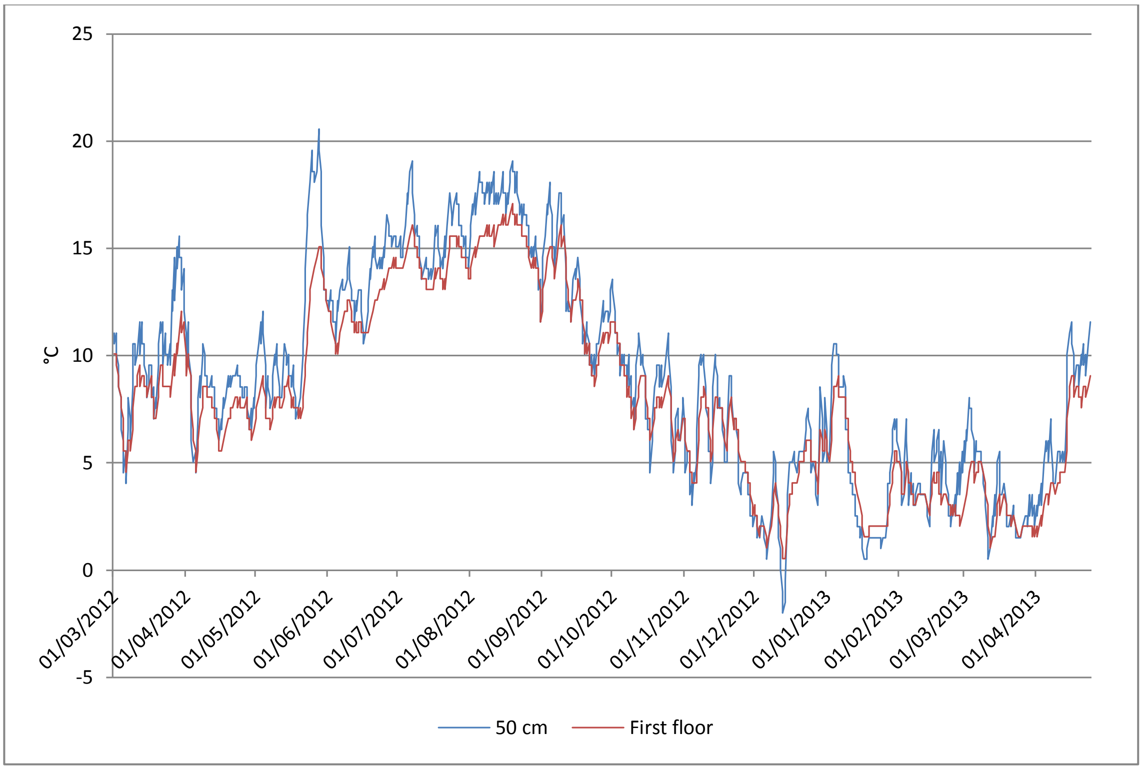


Fig. 8.6. Temperatures recorded within the north and west walls of the barn at Flatfield Steading.

The relative humidity data for two of the Schoolhouse locations is somewhat problematic until the latter part of April 2012. After April 26, however, the sensors were relocated because the relative humidity values obtained from the two lower locations were constantly around 100%. It is expected that standalone sensors might fail when exposed to such relative humidity levels for extended periods, becoming stuck and failing to record daily fluctuations thereafter. The abrupt drop in relative humidity at the beginning of April is explained by the fact that the sensor was taken outside, where conditions were drier and warmer, to download the data and was not re-installed for a few days (Aktas, pers. comm., 12/02/2014). No such problem was exhibited in the data captured using iButtons at Flatfield, which shows consistent differences between the relative humidity recorded at the two heights. A period of calibration is suggested by the divergence in data within the first four weeks that the iButtons were *in situ*, over which time the backfilled clay would have been drying out and affecting humidity levels internally. Nevertheless, there appears to be seasonal variation in the degree of difference between the two sets of data, with a trend towards convergence over the course of the winter months.

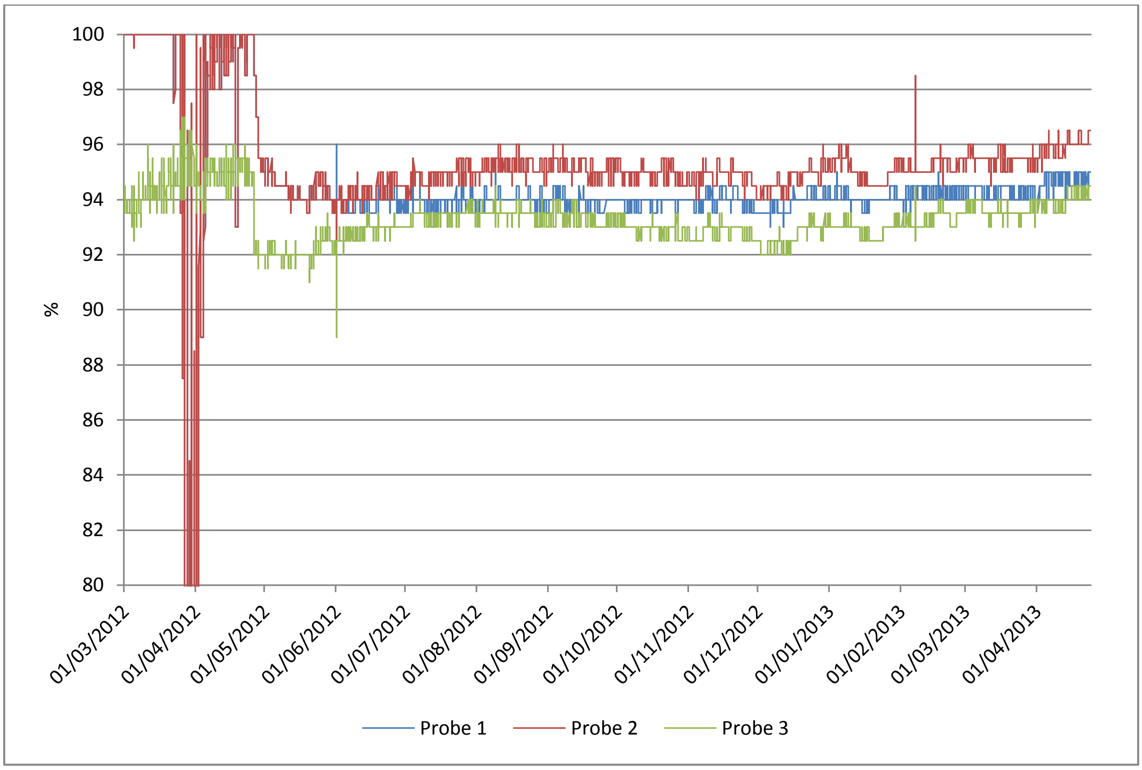


Fig. 8.7. Relative humidity data recorded within the west gable wall at Cottown Schoolhouse.

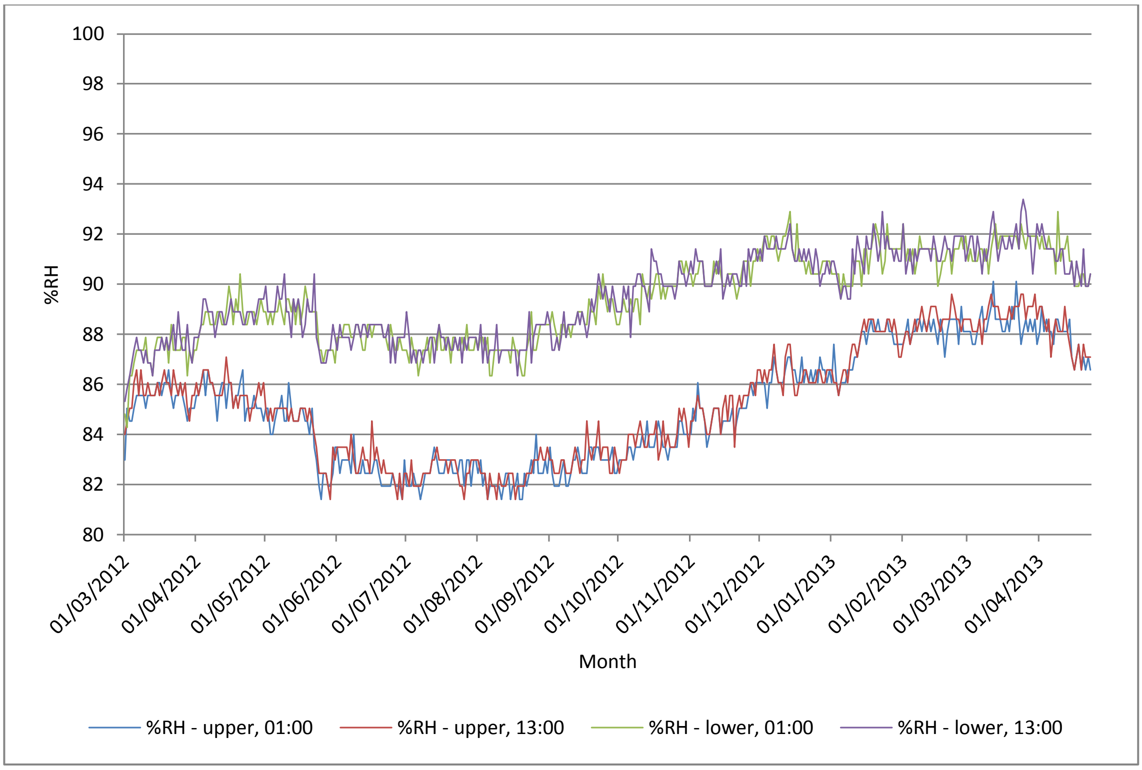
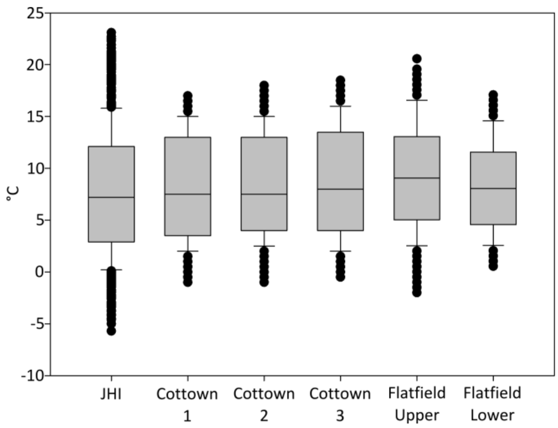


Fig. 8.8. Relative humidity recorded within the north and west walls of the barn at Flatfield Steading.

Removing the data for the Schoolhouse up to and including April 2012 demonstrates a consistency in the relative measurements recorded by each probe. Interestingly, the mid-height probe logged the highest relative humidity throughout, ranging between 92% and 98.5% with a mean of 94.9%, perhaps as a consequence of ingress from above due to thatch failure. This compares with means of 94.1% at the lowest level and 93.1% above the eaves. All three probes recorded higher relative humidity than at Flatfield, with exception to very limited crossover in the data for the higher probes from each structure, and with notably lesser range. This presumably reflects the impacts of increased levels of water ingress at Cottown resulting from both ground saturation and the potential failure of the thatch allowing water to seep from above. The difference between daytime and night time relative humidity recorded at Flatfield was negligible compared to the differences between the two locations, with the mean relative humidity at 50 cm being over 5% greater than at first-floor height. The maximum relative humidity recorded at 50 cm was 93.4% (25/03/2013, 13:00) and the lowest was 84.3% (02/03/2012, 01:00). At first-floor height the maximum recorded was 90.1% (12/03/2013, 01:00) and the lowest was 81.4%. This was recorded numerous times between June and September 2012.

Table 8.3. Summary table with data for Cottown with March and April 2012 omitted.										
	Old Schoolhouse, Cottown						Flatfield Steading Barn			
	1		2		3		50 cm		First floor	
	°C	% RH	°C	% RH	°C	% RH	°C	% RH	°C	% RH
Mean	7.9	94.1	8.3	94.9	8.6	93.1	8.2	89.5	9.1	85.2
Standard deviation	5.0	0.4	4.9	0.5	5.1	0.5	4.3	1.7	4.9	2.3
Min	-1.0	92.0	-1.0	92.0	-0.5	89.0	0.5	84.3	-2.0	81.4
Max	17.0	96.0	18.0	98.5	18.5	94.5	17.1	93.4	20.6	90.1
Range	18.0	4.0	19.0	6.5	19.0	5.5	16.5	9.1	22.6	8.7



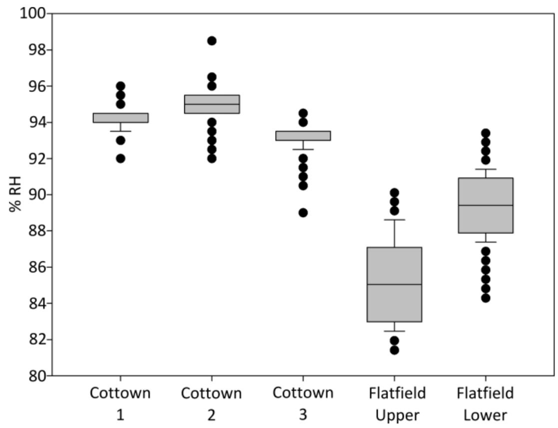


Fig. 8.9a (left). Variations in the temperature data collected within the walls of each site, shown in comparison with the spread of external temperature data for the sampling period. Fig. 8.9b (right). Variations in the relative humidity data collected within the walls of each site, with that for March and April 2012 omitted from the Cottown datasets.

8.2.2.1 Time series decompositions

A series of statistical analyses were developed, along similar lines to Cleveland *et al* (1990), to examine the underlying trends in the external weather and the temperature and relative humidity data collected from within the walls of each building, visually presented as a set of decomposed time series (Figs. 8.10a-e.). These were calculated and plotted using the time-series analysis functions of R statistical software (R Development Core Team, 2008). Each set of plots shows the original observations, underlying trends on weekly, monthly and quarterly bases and the variations within the trends over the course of the sampling period for each of the external weather parameters, including wind speed, and probes/iButtons. The plots are arranged in rows, with the top three rows for all sets of graphs exhibiting external temperature, relative humidity and wind speed, respectively. The bottom two rows show temperature and relative humidity data for each of the probes/iButtons at each location. It should be noted again that the relative humidity data for the two lower probes at Cottown is interpolated for the first two months using the mean monthly data for March and April 2013.

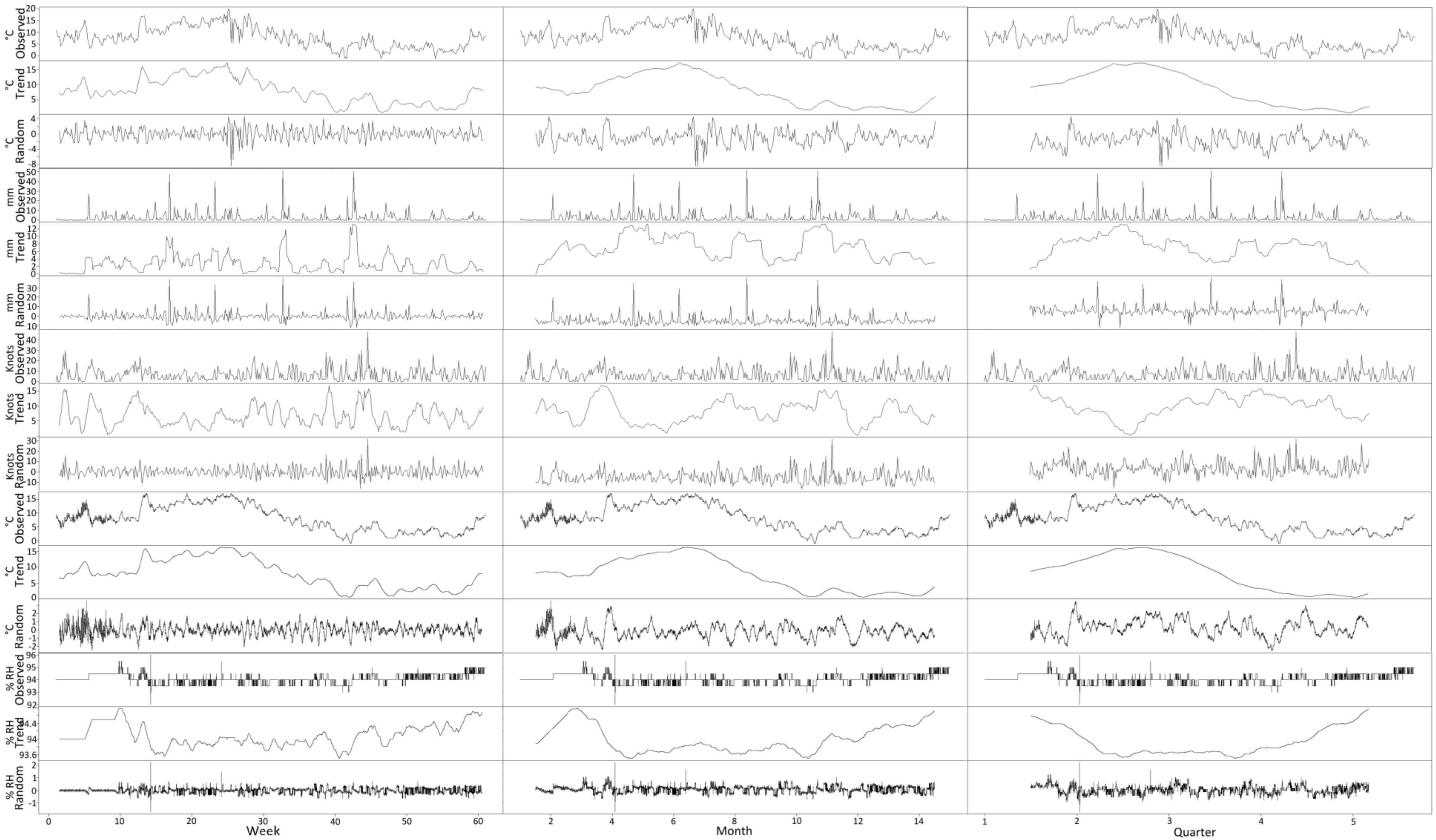


Fig. 8.10a. Time series decompositions: external conditions versus Cottown Schoolhouse Probe 1 data.

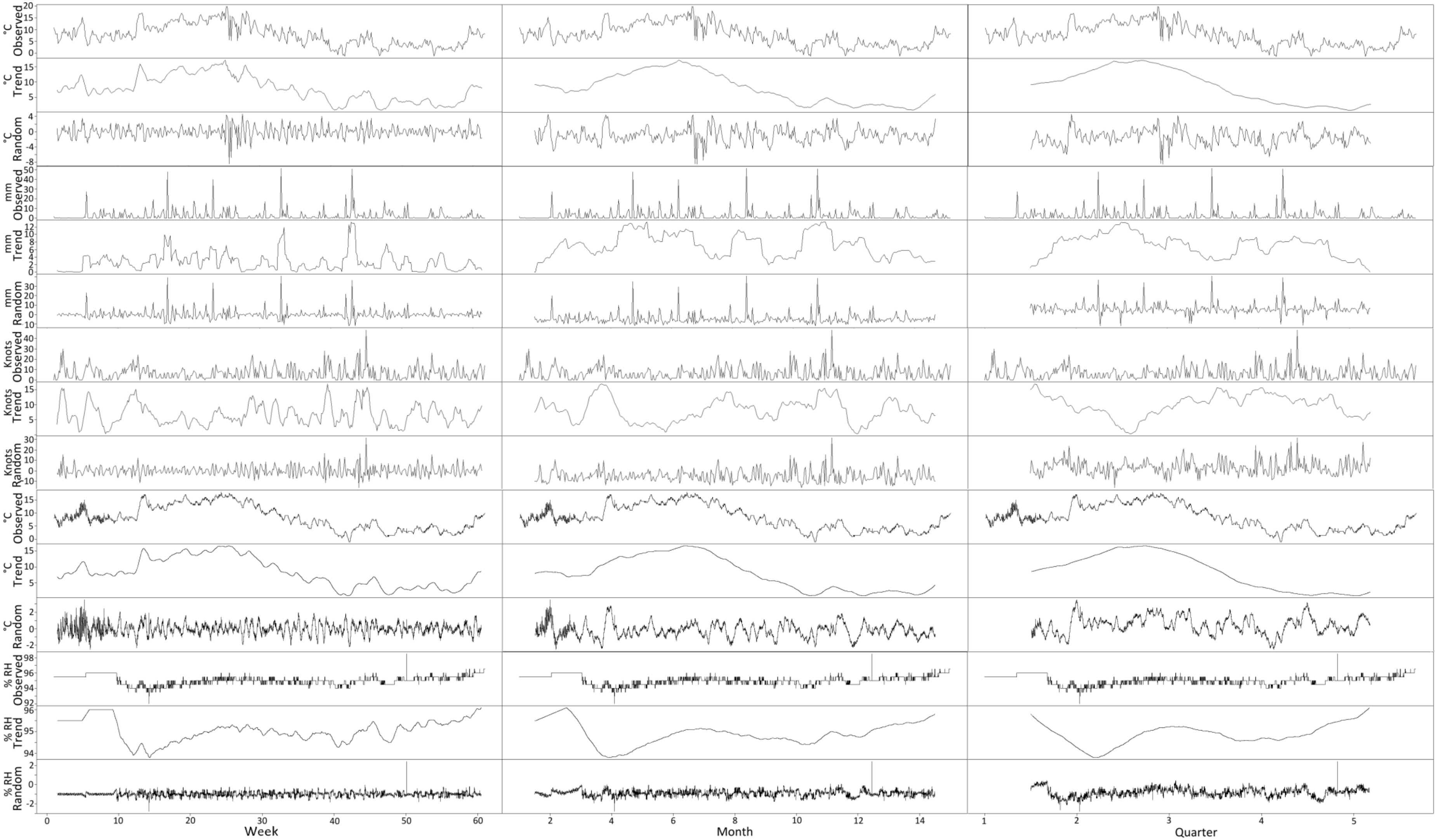


Fig. 8.10b. Time series decompositions: external conditions versus Cottown Schoolhouse Probe 2 data.

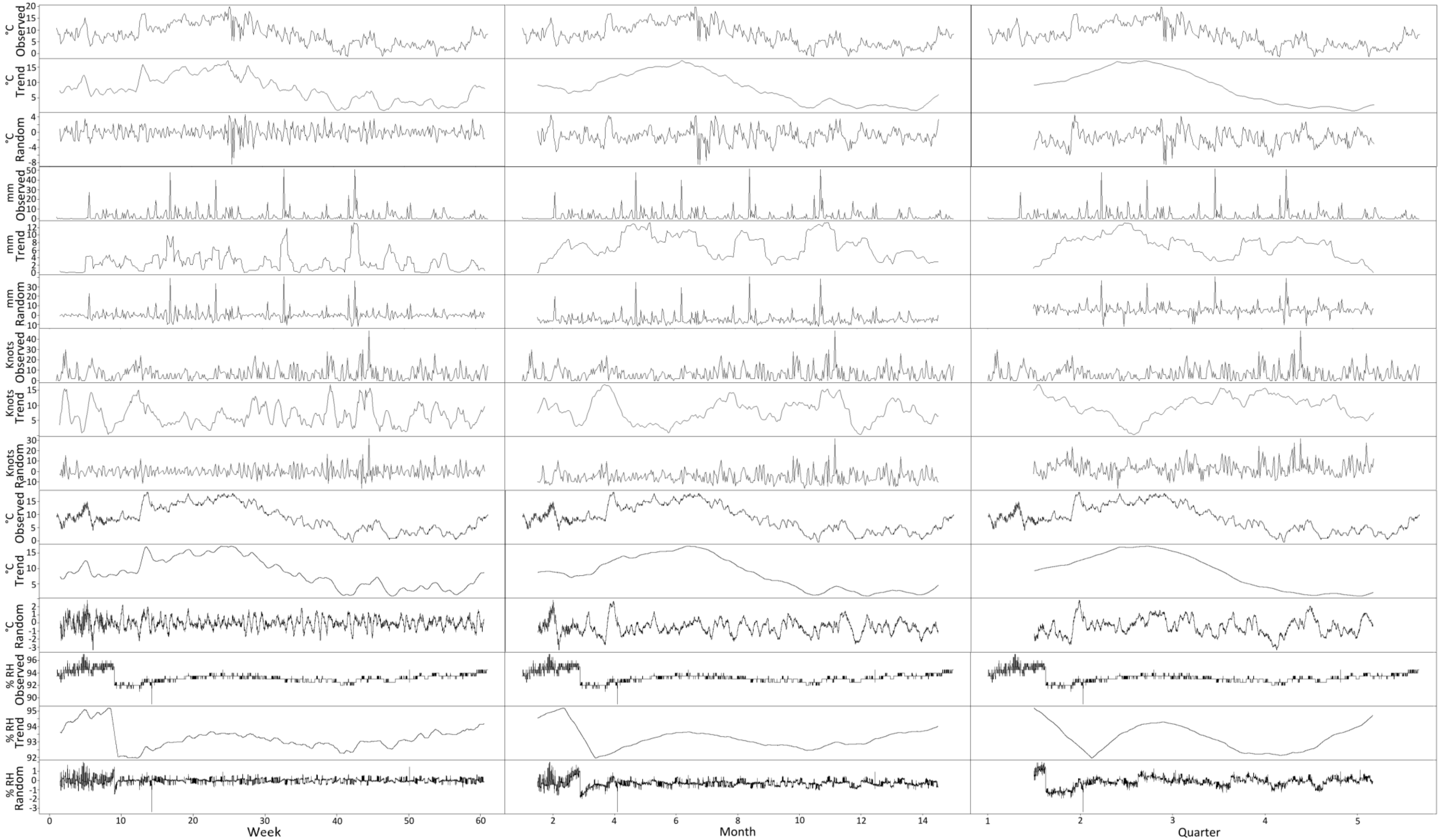


Fig. 8.10c. Time series decompositions: external conditions versus Cottown Schoolhouse Probe 3 data.

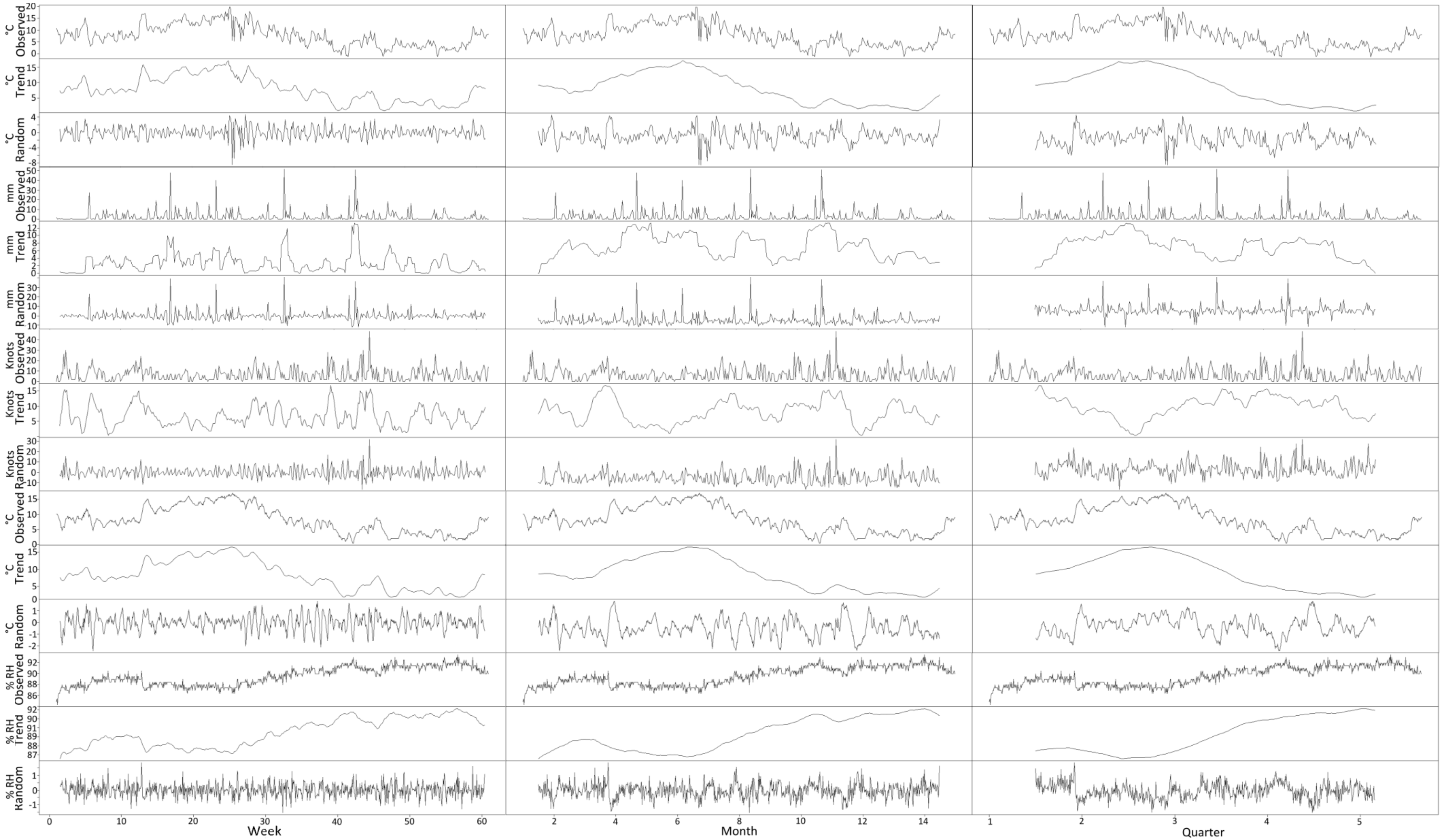


Fig. 8.10d. Time series decompositions: external conditions versus Flatfield 50 cm data.

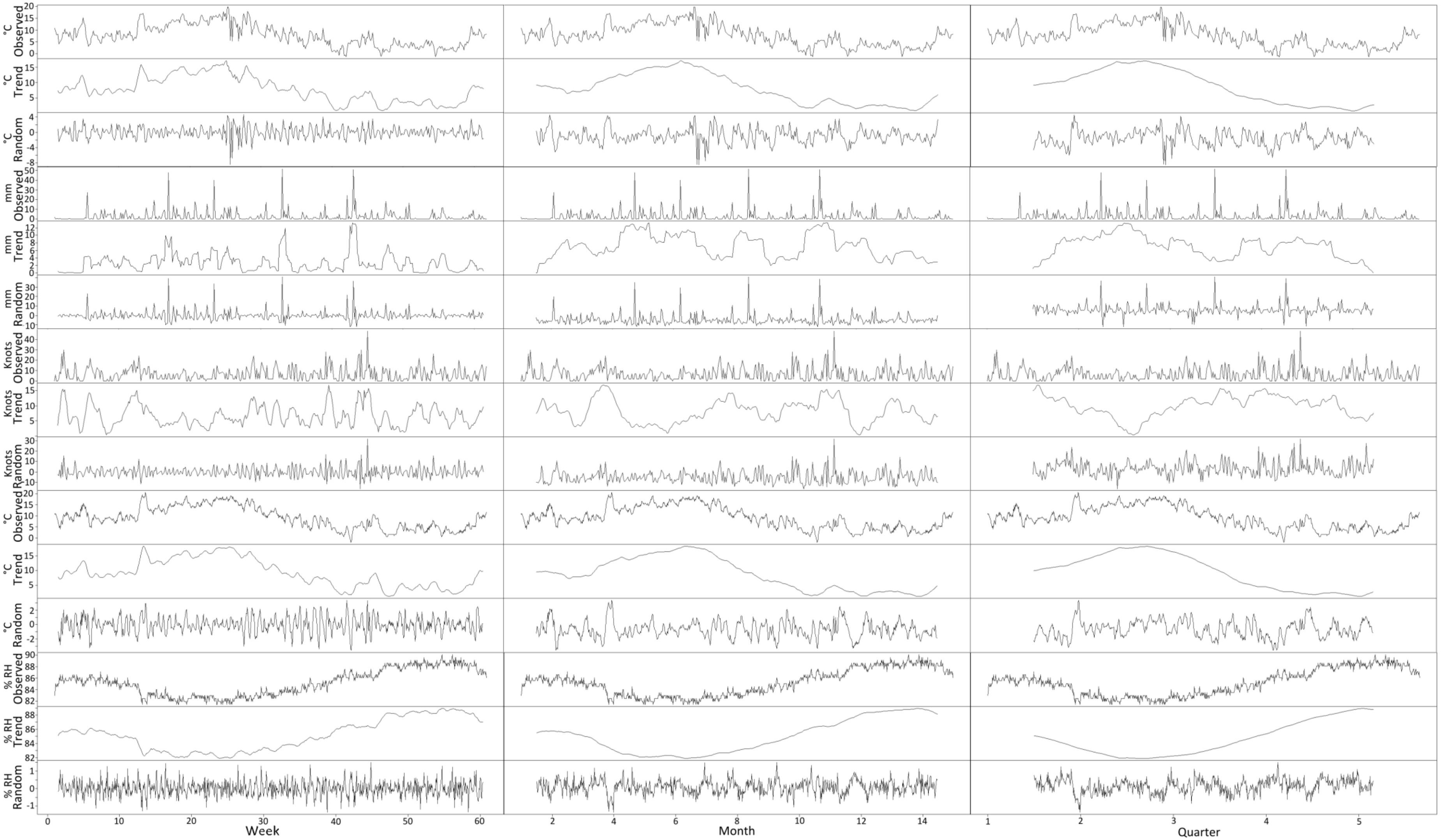


Fig. 8.10e. Time series decompositions: external conditions versus Flatfield first floor data.

Examination of the time series plots indicates some interesting trends in the patterns of weather over the period of interest and how the conditions within the walls of each structure responded. The prolonged depression of temperature in March 2012 is expressed clearly in the seven-day trend plots but is absorbed in the monthly and quarterly trends. An inverse relationship between temperature and wind speed is suggested, which tallies with expectations of greater stability in weather during the summer months. The lowest wind speeds are also recorded concurrently with extremely high precipitation in summer 2012. As already noted, this did not lead to any known flooding at the site and this therefore suggests that efficient evaporation of water from around the site is reliant mainly upon temperature. Increased wind speed in winter periods has direct impacts in terms of increased incidences of rain being driven onto the walls of the buildings during a time of vulnerability. This is especially relevant to the western gable at the Schoolhouse as the prevailing winds in the Carse of Gowrie are from the south-west. Of particular utility, however, are the decompositions of precipitation data, which are difficult to interpret when presented as daily observations alone as the eye tends to be drawn to the most pronounced spikes without fully appreciating the effects of lower-level precipitation. The trend plots give visual insight into the potential for individual rainfall events to become cumulative phenomena within the year, with the moving averages showing distinct blocks of precipitation derived from continuous mean data over each chosen period. It should be noted here that some of the extended implications for this accumulation of rain water are discussed in relation to the results of MMS sampling (8.2.3.).

As would be expected there is a clear correlation between the temperatures recorded externally and within the walls of each structure, with the known lag in response being too short to notice over the long-term plots. It is worth noting that the data for the probes at Cottown include a period of increased randomness during the same time as when relative humidity values were recorded incorrectly. More interestingly though, the relative humidity data recorded by the lowest probe within the Schoolhouse flat-lines until well into the third quarter of the time series, whereas a pronounced hump is exhibited between the middle of the second and third quarters for both of the other locations. The rises of these humps both occur when temperature is reaching its summer peak, precipitation levels are falling and wind speed is at its lowest. It should be noted, however, that precipitation remains noteworthy throughout this time, even if exhibiting a falling trend, and these humps in relative humidity for the data recorded higher in the wall may indicate water ingress from above due to a failure of the thatch. The fact that the lower probe does not show any increase in relative humidity over the same period corroborates the suggestion that groundwater threats are alleviated by increased summer evaporation rates. For the period in which the higher probes at the Schoolhouse show elevations in their relative humidity data, the iButton data from Flatfield remains smooth and follows the expected seasonal trend, which seems to support the possibility of water ingress from above being picked up in the Schoolhouse data. The relative humidity for the lower part of the Flatfield wall shows a slightly earlier and more accelerated increase from the latter part of the second quarter when compared with that for the higher part of the wall. This presumably reflects the impacts of increased uptake of groundwater as temperatures fall and external relative humidity rises concurrently, with only the latter phenomenon being expressed through the data for the higher iButton.

8.2.3 Microwave moisture sensor (MMS)

MMS survey was chosen as a suitable means of achieving the non-destructive assessment of variations in ground water uptake into the mudwalls of the Old Schoolhouse, particularly targeted over the course of the winter-spring transition. The application of this apparatus in heritage studies is still relatively novel, undoubtedly so in relation to earthen materials, and provided an efficient means of chronologically tracking relative changes to moisture across large wall surface areas without the need to necessarily calibrate for different densities (Phillipson *et al.*, 2007). The successful application of this technology has been demonstrated in relation to mapping routes of water ingress within the walls of sites such as Kisimul Castle, Scotland (Young, 2013). The procedures and results described in this thesis demonstrate the applicability of the technique in a novel context and deliver outcomes useful to further understanding the response of the structure to climate-related pressures.

Following a number of preliminary sampling events used to ascertain the applicability of the apparatus, periodic sampling of the relative moisture content within the north and west walls was conducted between November 2012 and April 2013 using a Moist300B microwave moisture meter with Moist-PM volume sensor head (HF Sensor GmbH, Leipzig, Germany), factory-calibrated for use with building materials of varying density. The apparatus utilises a dielectric method, using the differences in permittivity between a solid material and the water content held within it and the dielectric loss of water content induced by the microwave field emitted to calculate measurement values. The development of this apparatus using microwave technology overcomes problems identified in previous studies of portable dielectric soil moisture probes, where the degree of electrode protrusion and smoothness of the soil surface directly impacted on the results obtained (Morgan, Wood and Holmes, 1993).

The north and west walls were chosen in part because of their accessibility and the fact that they are orientated on the same lines as those walls instrumented with iButton probes at Flatfield Steading. Most important, however, was the need to monitor the west gable wall as it is particularly susceptible to moisture uptake, with the north wall acting in part as a reference.

Using the chosen sensor head, the microwaves penetrate to a depth of ~30 cm with a ~15 cm radius and the sensor head registers the extent of the microwave that is reflected by the moisture content within the solid material. This means that individual readings correspond to mean relative moisture content for the internal volume of each sampled point. Sampling was thus conducted on a 30 x 30 cm grid pattern to a height of 220-250 cm, working in columns along each wall from left to right. No samples were taken from below a height of ~15 cm so as to avoid any interference from the ground.

Fig. 8.11. MMS sampling along the north wall of the Old Schoolhouse, Cottown, with diagrammatic example of the “balloons” of microwaves emitted by the moisture meter sensor head.

It should be noted that the MMS was used without being specifically calibrated for use with mudwall material, this being an unavoidable drawback determined by a lack of available materials with which calibration could be achieved. Ridout (2008) has discussed a variety of moisture monitoring techniques relevant to earth buildings, noting certain problems that have to be recognised such as the pragmatics of buying costly instrumentation, the effects of interference from salts or the difficulties of calibrating for building materials that can vary greatly between sites, even if they are of the same basic typology,. Pinchin (2009) has discussed the practical compromises made when sampling historic walls in the field, questioning the infallibility of calibration. The objectivity of this point is emphasised when consideration is afforded to the material variability inherent to mudwall structures, sometimes within small geographic regions. More pertinently, however, preliminary sampling events carried out at the Schoolhouse demonstrated a good level of consistency in results. Furthermore, consistency in sampling procedure was maintained throughout the monitoring period and it was deemed that shifts in relative values are entirely valid and informative at the intra-site level. The measurements are given on a relative scale from 0 (completely dry) to 4000 (completely saturated). Conclusions based upon absolute values for water content within the walls are avoided.

The results of MMS sampling are presented in summary table (Table 8.4) and as area plots by month, means over time and standard deviations over time (Figs. 8.12 and 8.13). Across both walls and each sampling event the mean measurements for the bottom third were the highest (wettest) and those of the top third the lowest (driest), with exception of the north wall measurements for November and April where the middle third was driest. This would seem to add credence to the suggestion from the probe data of water ingress from above. The highest mean and maximum measurements for both walls were recorded in January 2013, as were the greatest deviations from the mean. This pronounced increase in deviation in January reflects the increased moisture measurements towards the base of the wall, as highlighted in the area plots. The north wall appears to have retained greater moisture at its eastern and western ends, drying in the middle part. Although 73.3 mm of the 100 mm of rain recorded for January 2013 fell after the sampling date of 17 January, it was noted when sampling was conducted that the ground around the Schoolhouse was at this point already saturated, with surface water gathering around the porch on the south wall, thus corroborating the suggestion of accumulated impacts of rainfall depicted through time series decomposition of the data. It seems that the flooding of the Schoolhouse in late-January was therefore a consequence of the combined effects of colder winter temperatures and prolonged, persistent rainfall (as reflected in mean monthly precipitation for December. The west wall was wetter overall at each time of sampling other than in March, when the north wall retained a greater degree of wetness in the lower and middle thirds. Interestingly, the moisture values for middle and top thirds of the west wall fell between November 2012 and January 2013, whilst the bottom third was at its wettest. It would seem that the cumulative uptake of water following winter precipitation is most pronounced in the data for the west wall. The mean values over time indicate that the lower thirds of both walls were consistently wetter than other wall areas.

Table 8.4. Summary table of MMS sampling results, showing mean measurements and standard deviations across varying height within the walls for each sampling date, minimum, maximum, overall mean and standard deviation (SD) values for each sampling date.

	North wall									
	Means per third (distance from ground level)			SD per third						
Date	10-70 cm	100-130 cm	160-220 cm	10-70 cm	100-130 cm	160-220 cm	Min value	Max value	Mean across wall	SD across wall
28/11/2012	1474.4	1216.4	1301.4	169.5	202.3	113.5	788	1891	1349.5	190.7
17/01/2013	1955.7	1386.4	1337.3	206.4	262.8	129.9	979	2443	1590.0	353.3
20/03/2013	1767.9	1485.5	1280.2	241.4	232.2	159.6	888	2295	1517.6	301.3
24/04/2013	1341.1	1223.2	1326.5	175.1	161.2	128.7	803	1822	1308.6	162.1
	West wall									
	Means per third			SD per third						
Date	10-70 cm	100-160 cm	190-250 cm	10-70 cm	100-130 cm	160-220 cm	Min value	Max value	Mean across wall	SD across wall
28/11/2012	1748.4	1635.8	1561.9	206.9	126.5	176.2	937	2238	1648.7	188.6
17/01/2013	2046.3	1570.1	1405.3	254.5	274.4	162.0	854	2688	1673.9	359.3
20/03/2013	1567.6	1438.4	1371.2	206.2	124.3	107.8	914	2077	1459.1	172.2
24/04/2013	1408.0	1391.3	1345.2	121.4	117.0	103.9	980	1706	1381.5	116.9

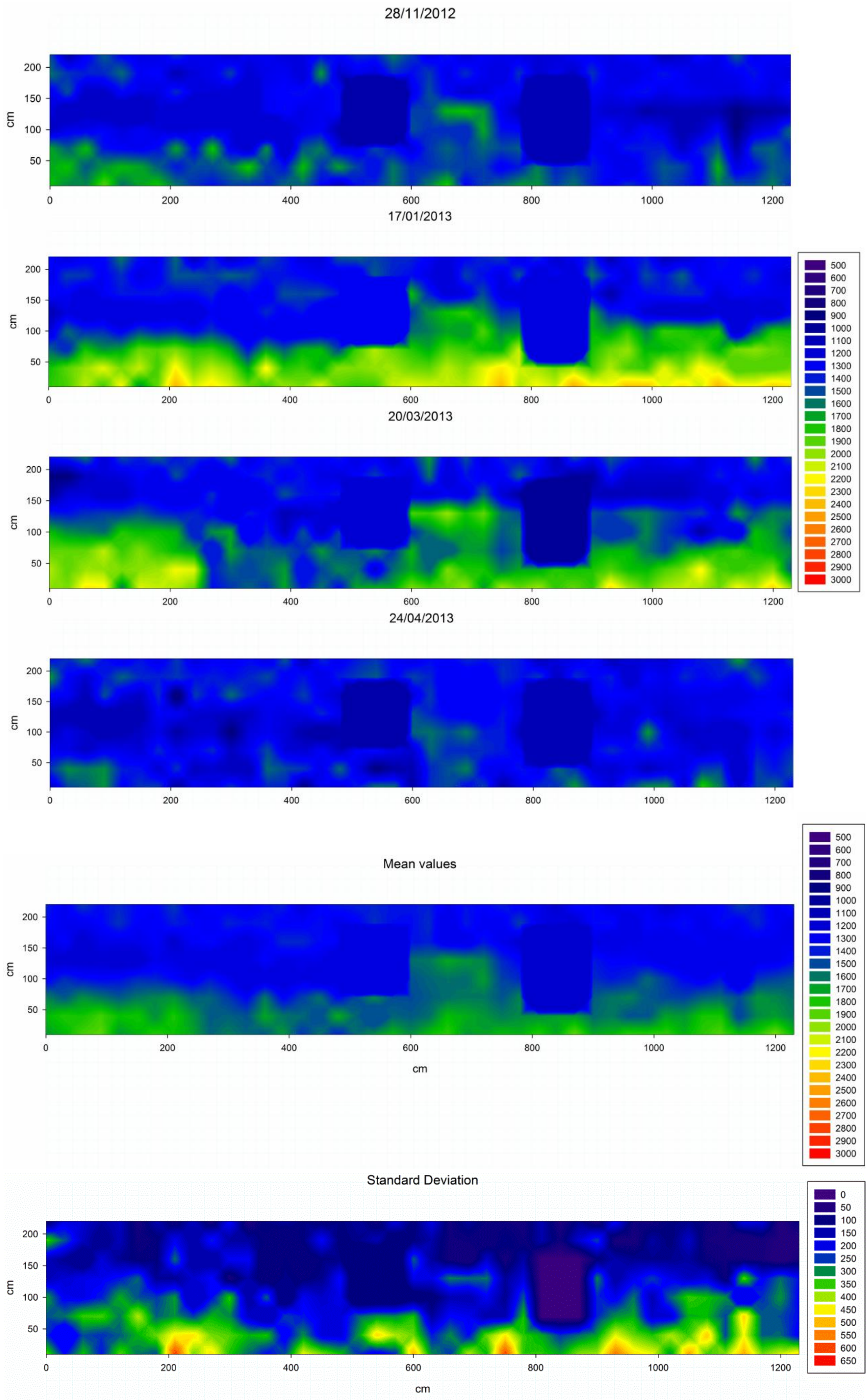
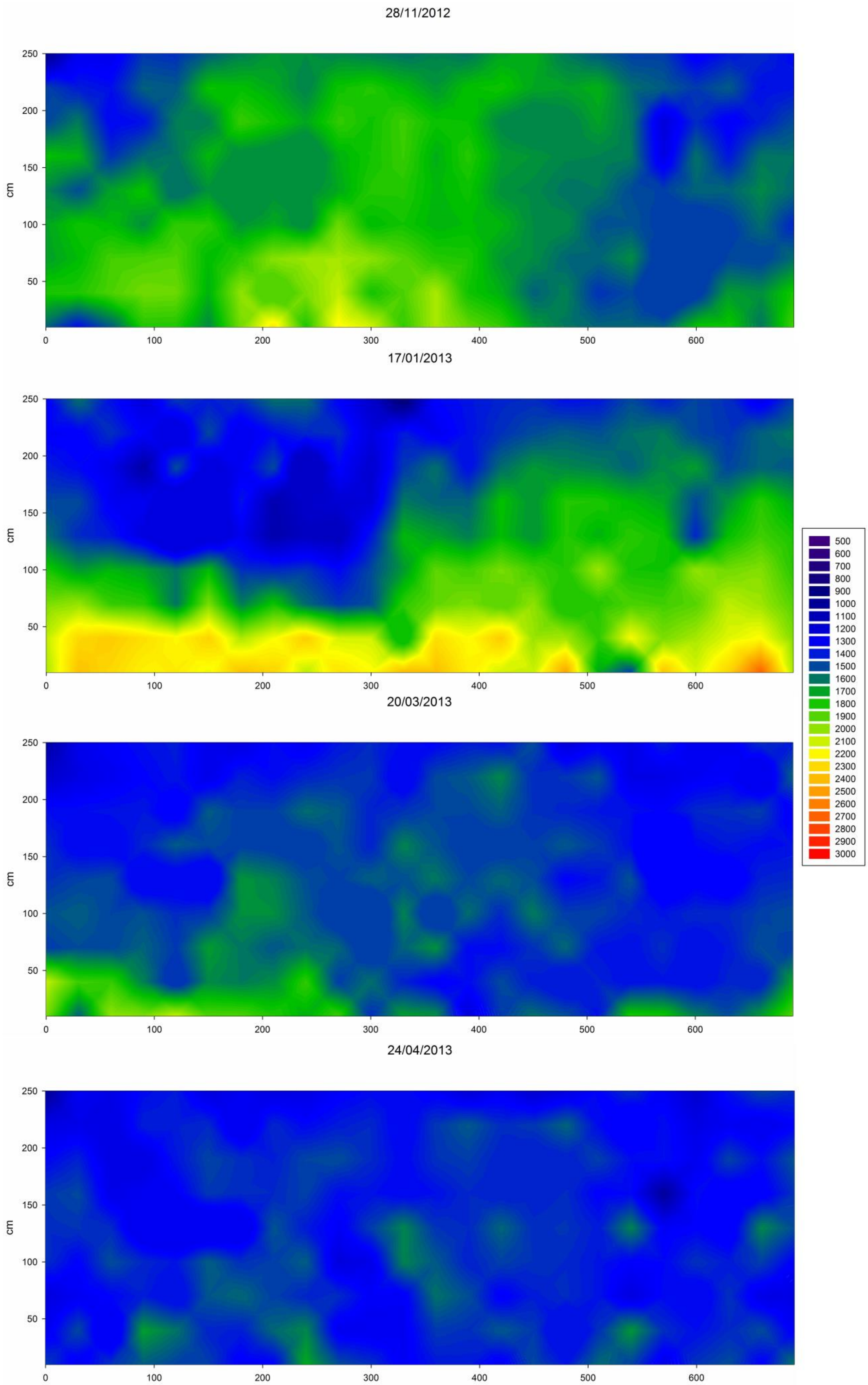


Fig. 8.12. MMS values in the north wall for each sampling date, mean and standard deviation over time.



28/11/2012
17/01/2013
20/03/2013
24/04/2013
cm
250
200
150
100
50
0
100
200
300
400
500
600
500
600
700
800
900
1000
1100
1200
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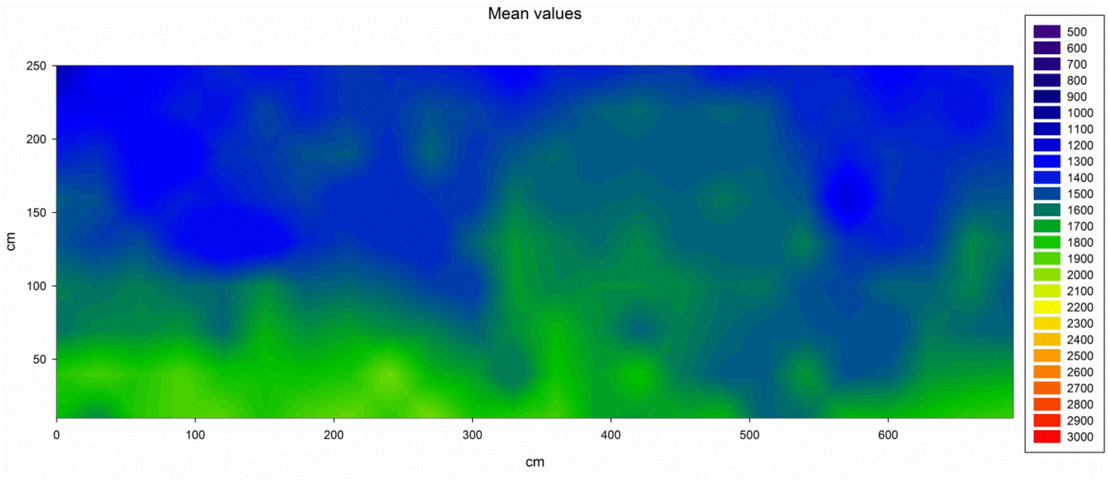
3000



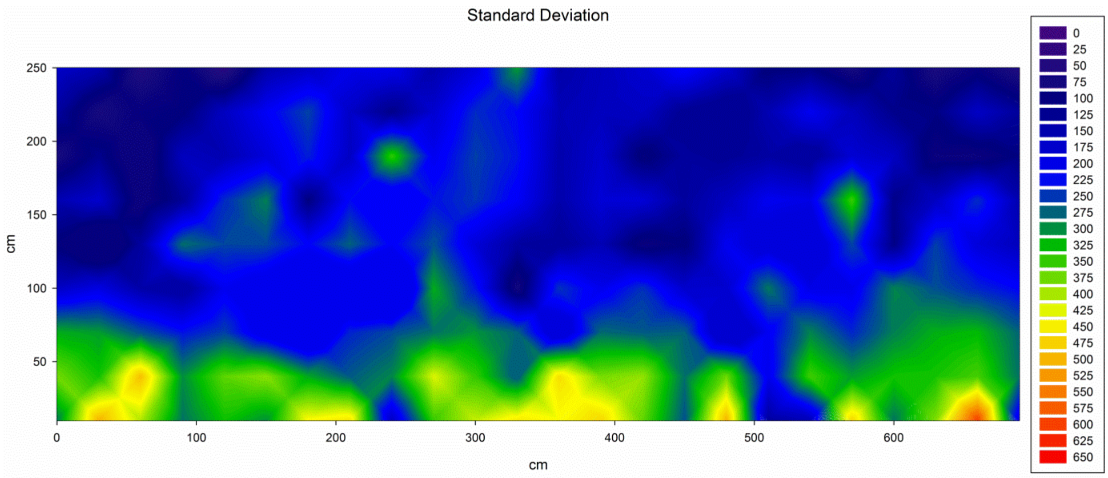


Fig. 8.13. MMS values in the west wall for each sampling date, mean and standard deviation over time.

Plotting the mean measurements for the relative wetness in the bottom third of the two walls at each sampling date against concurrent daily precipitation indicates that accumulated levels of precipitation should be considered when assessing increased MMS values. It should be noted that the highest values for each wall, recorded on 17/01/2013, are clearly preceded by a number of relatively dry days (Fig. 8.14), whilst the samples collected in November and March were preceded by more immediate precipitation events.

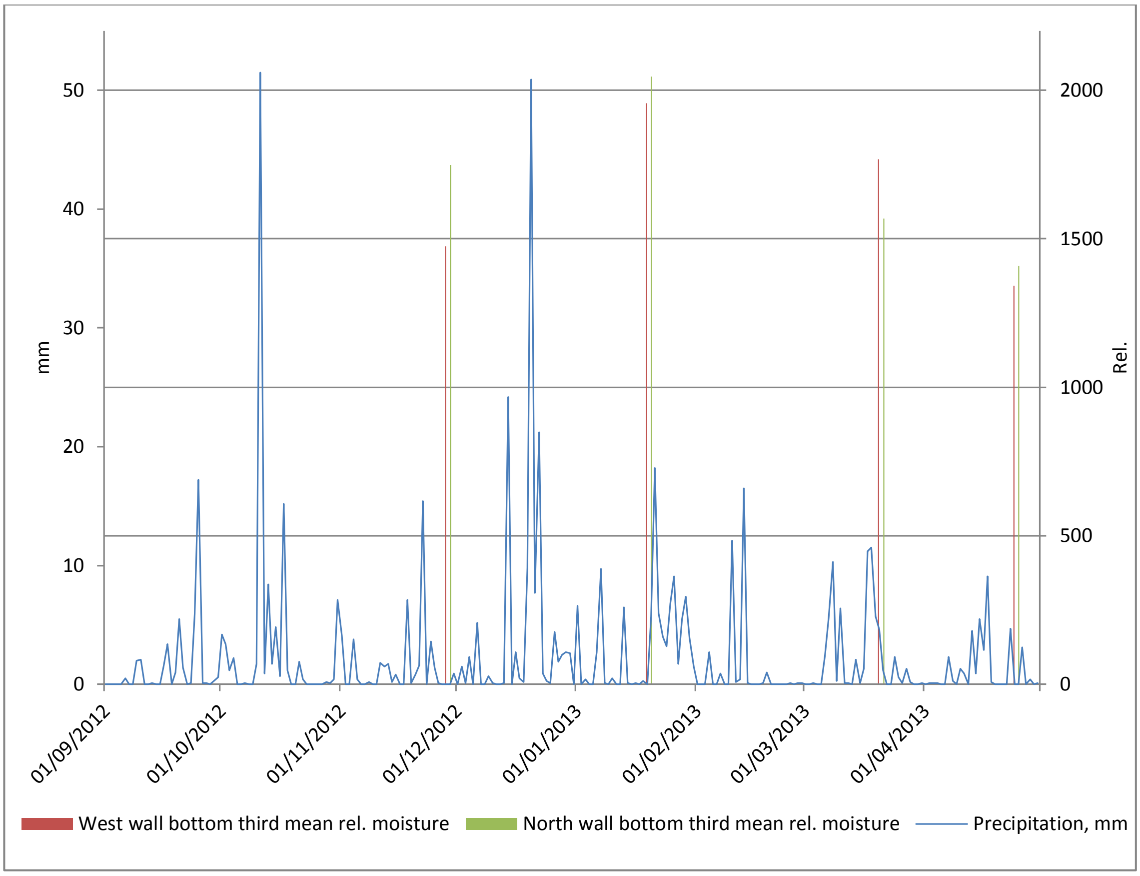


Fig. 8.14. Daily precipitation and MMS values recorded for the north and west walls.

It is important to note that, although the highest levels of precipitation across the period were recorded for December 2012, almost three-quarters of the precipitation for January 2013 fell after the sampling date of 17/01/2013. It is possible to investigate the potential for accumulated impacts of precipitation on the wetness of the bottom third of each wall by noting the dates at which measurements were taken on time series plots decomposed over seven-day, fourteen-day and thirty-day periods (Fig. 8.15). Clear implications emerge from this regarding the combined effects of increased rainfall over longer periods together with decreasing temperatures over the course of the winter months.

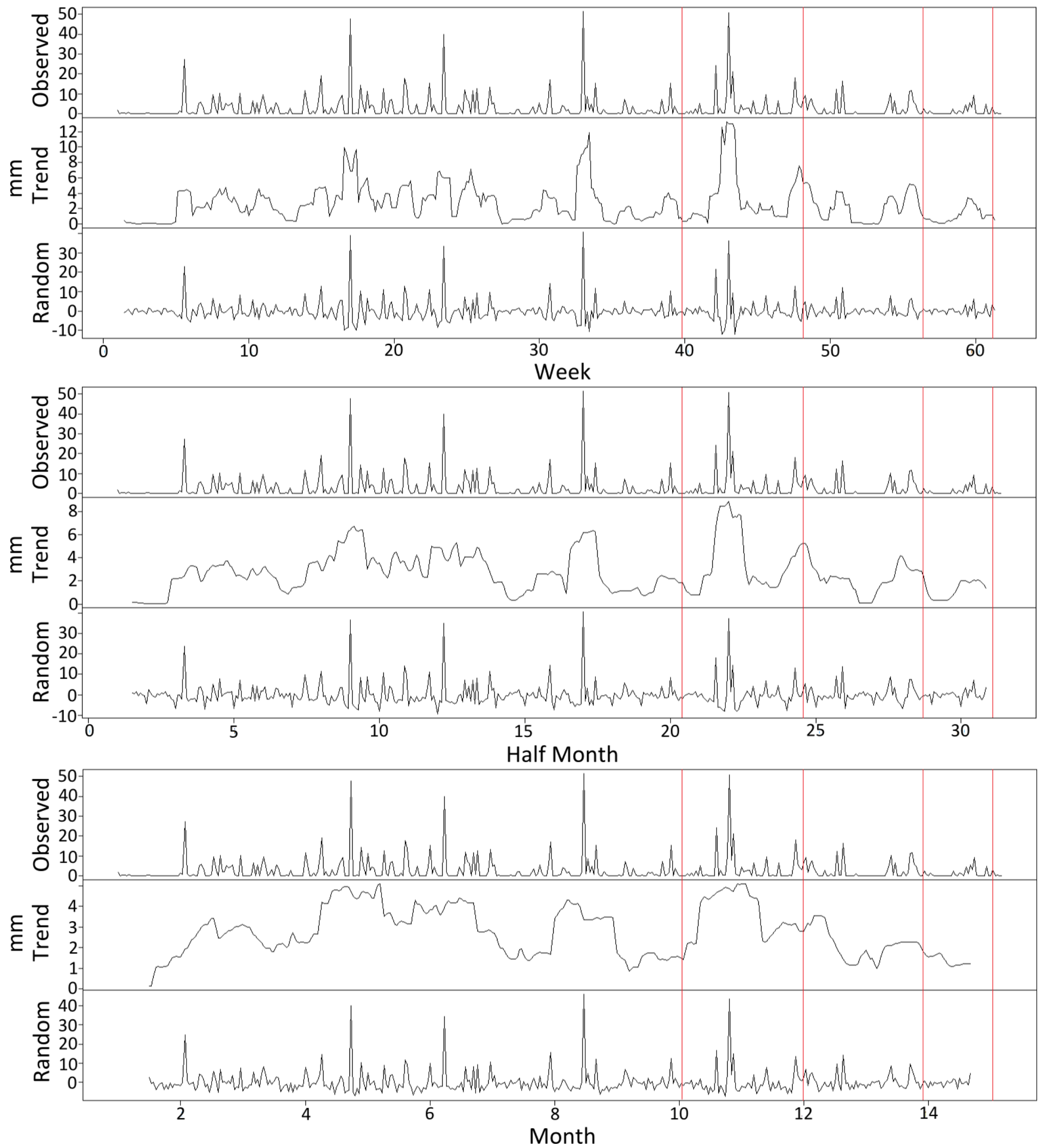


Fig. 8.15. Time series decompositions of daily precipitation records, with approximate dates of each MMS sampling event indicated by red lines.

8.3 Conclusion

The investigations outlined here represent a novel and easily replicable approach to directly assessing the responses of mudwall buildings to external weather conditions. Although the winter-spring of 2012-2013 may not be representative of future predicted conditions in respect of winter freezing events (there are likely to be fewer still), it reflects the predicted increase in the regularity of extreme events, thus making it a useful case study. Indeed, some pronounced responses to the observed conditions are seen in the data for each of the methods applied.

The temperature and relative humidity loggers at both locations indicate a number of noteworthy results. Perhaps most enlightening is the resilience of the mass earth walls to extremes of temperature, particularly freezing conditions that are shown through the experimental studies outlined earlier to have potentially disastrous impacts. The use of time series decompositions adds another layer of inference to be drawn from the raw data acquired at each site and can be used to indicate trends at whatever timescale may be required. When used alongside the results of MMS sampling it is clear to see the variability in moisture retention within the walls depending on temperature and the cumulative impacts of precipitation over a number of weeks. It would prove illuminating to extend these investigations and thus integrate the results more completely by conducting MMS sampling on a more regular basis and aligning a greater number of results with the time series decompositions. The relative humidity readings also picked up increases in moisture in the lower parts of each wall as a consequence of ingress through capillary rise, although this is merely indicative and does not demonstrate the response of the walls *en masse* in the same way as the MMS data. The use of temperature and humidity probes would allow for inter-site comparisons across wide geographic areas and building materials. MMS, however, could only be used with confidence on the intra-site level, with consistency in approach critical, due to issues of calibration. It would seem, however, that this is a criticism of the apparatus that stands across all building material types, due to the inherent variations in sandstone, brick or concrete as generic material groups that the apparatus is factory-calibrated for use with. It would prove informative to instrument a structure with iButton probes in a greater number and variety of locations than was done at Flatfield Steading, where the approach was deliberately conservative in order to adhere to the owners' request to limit the removal of material. A more intrusive approach is currently being undertaken at “Archibald Moffatt’s house” in Moffat, Dumfries and Galloway as part of another project.

The regularity and intensity of flooding events at the Old Schoolhouse have increased in recent times and these will, according to climate projections, become increasingly common over the twenty-first century, thus heightening worries over the future of the structure. It seems important, however, to recognise the likelihood that historic flooding events at the site would have occurred with at least some regularity in the two-and-a-half centuries since its erection, given its geological and topographical context. The survival of the building would thus suggest some degree of resilience to water-related deterioration. Despite containing some apparent anomalies, which could be the result of artefacts due to repair work, the MMS data highlights the dynamism of water ingress into and release from the targeted mud walls of the Schoolhouse. The reaction of the walls to levels of precipitation is striking and the interplay between temperature and precipitation levels is also significant. The overall mean readings show a degree of uniformity in moisture content across each wall, yet it is clear that during wet periods the lower portion takes up more water from below. This is reflected in the plot of the standard deviation of these data. The greatest variation in moisture content is seen within a height extending to 1 m above the ground surface, suggesting that the effects of the high water table and episodic flooding events are in part dissipated by the action of capillary rise within the wall fabric to this level. Forster *et al.* (2008) have suggested that the action of capillary suction can improve the strength of inter-particle bonds within mudwall materials while they remain unsaturated and it may be the ability of the walls at Cottown to draw water up from the ground that aids resilience.

Having considered the climate and weather of the Carse of Gowrie and observed some of the macro-scale impacts of conditions at the Schoolhouse and Flatfield, the investigations are in the following pages focused towards the micro-scale, moving from the results of X-ray diffraction tests made upon material from Cottown and *in situ* measurements made at the site using portable X-ray fluorescence, to micromorphological and micromorphometric analyses of sampled and experimental materials. This includes the novel use of X-ray computed tomography scanning as an adjunct to the assessments of materials taken from the Schoolhouse.

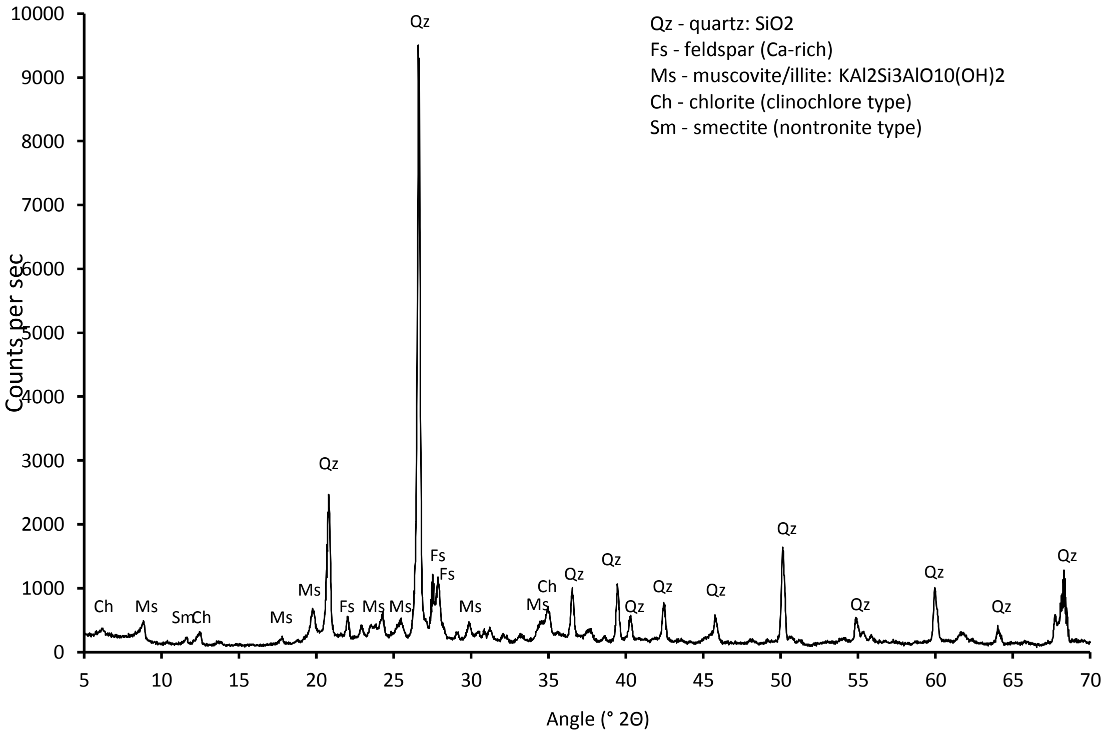
9. X-ray diffraction, portable X-ray fluorescence and near infrared spectroscopy analyses of earth materials

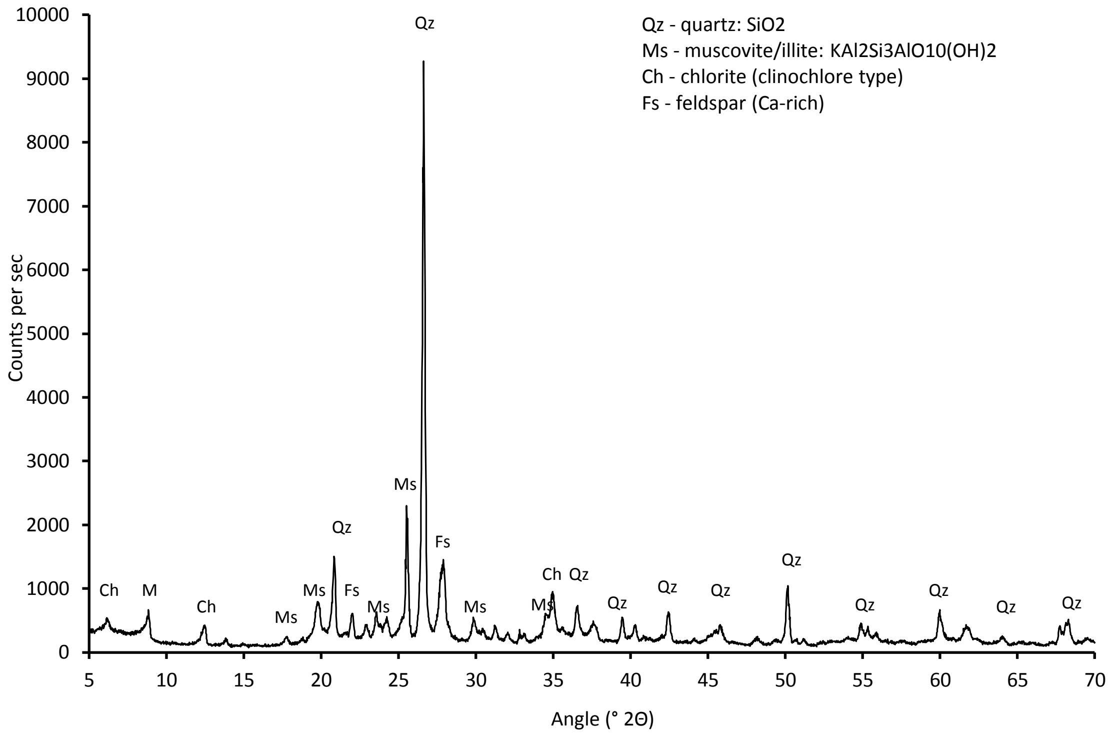
9.1 Introduction

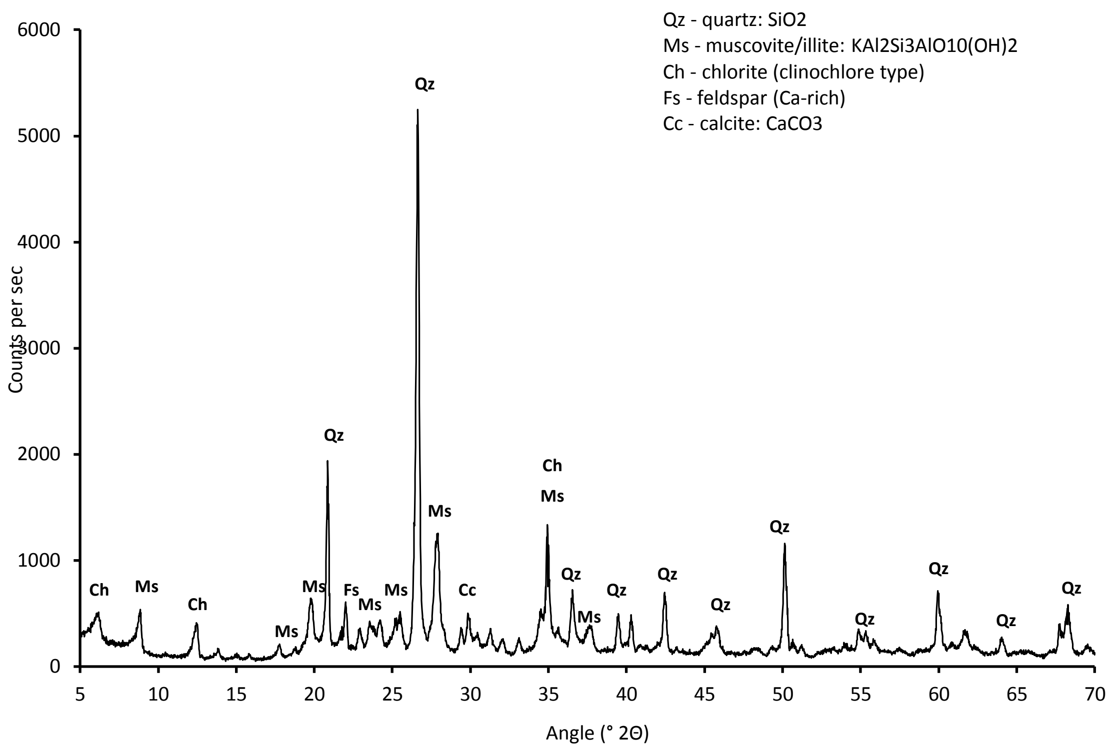
X-ray methods can be used to characterise the physical attributes of heterogeneous materials, helping to validate subsequent optical analysis techniques, and provide means of examining chemical changes at the micro-scale. Precedence for the integrated application of these technologies can be found in contexts far removed from Scotland, with insights being used in conservation management plans. Marcus (2012), for example, used X-ray diffraction (XRD) in combination with X-ray fluorescence (XRF) in the characterisation of historic earth building materials in Abu Dhabi, with a view to informing decisions as to the use of repair materials. Similar applications have been discussed in relation to the composition of traditional earth mortars and adobe bricks (Coroado *et al.*, 2010; Fratini *et al.*, 2011) with a view to informing conservation and restoration initiatives. The use of portable XRF in tracing surface changes to flood-affected walls, however, is a novel application that offers further insights into the processes of mudwall deterioration following episodes of excessive water ingress.

9.2 X-ray diffraction (XRD)

XRD has been widely used since the 1960s as a means of identifying clay and non-clay minerals present in a heterogeneous material, although the relative abundance of clays may only be approximated. Greater clarity of differentiation between the clays present may be achieved through pre-treatments such as the removal of carbonates and of organic materials. The samples analysed here were subject to the more minimal pre-treatment of grinding to a fine powder (<500 µm) prior to analysis. Bulk samples acquired using scrapings and materials that were already structurally separate from the main body of the mudwall at five locations around the western room of the Schoolhouse were analysed using an ARL X'TRA powder XRD system (Thermo Fisher Scientific Inc., Waltham, MA, USA). The ground samples were mounted on a spinning stage, with data collected over the 2θ range 5° to 70° at a rate of 1° per minute. The X-ray wavelength was 1.54 Å. Results (Fig. 9.1) indicated the consistent presence of quartz, muscovite/illite, chlorite, feldspar and calcite. One exception was identified in the region of 27.9° 2θ, where in four of the samples a double peak indicates the presence of both feldspar and muscovite/illite. In the remaining sample there appears only a single peak attributed to muscovite/illite. The presence of illites and smectites in the Stirling Association clays has been noted already (Wilson *et al.*, 1984). The predominance of illite in the fine fraction of clay sourced from the Errol Brickworks when compared with soils used in the commercial manufacture of Ibstock and Raeburn unfired earth bricks has been reported by Galán-Marín *et al.* (2010). Some swelling smectite group clays were apparent in two areas.




Qz - quartz: SiO2
Ms - muscovite/illite: KAl2Si3AlO10(OH)2
Ch - chlorite (clinochlore type)
Fs - feldspar (Ca-rich)
Counts per sec
Angle (° 2Θ)


Qz - quartz: SiO2
Ms - muscovite/illite: KAl2Si3AlO10(OH)2
Ch - chlorite (clinochlore type)
Fs - feldspar (Ca-rich)
Cc - calcite: CaCO3
Counts per sec
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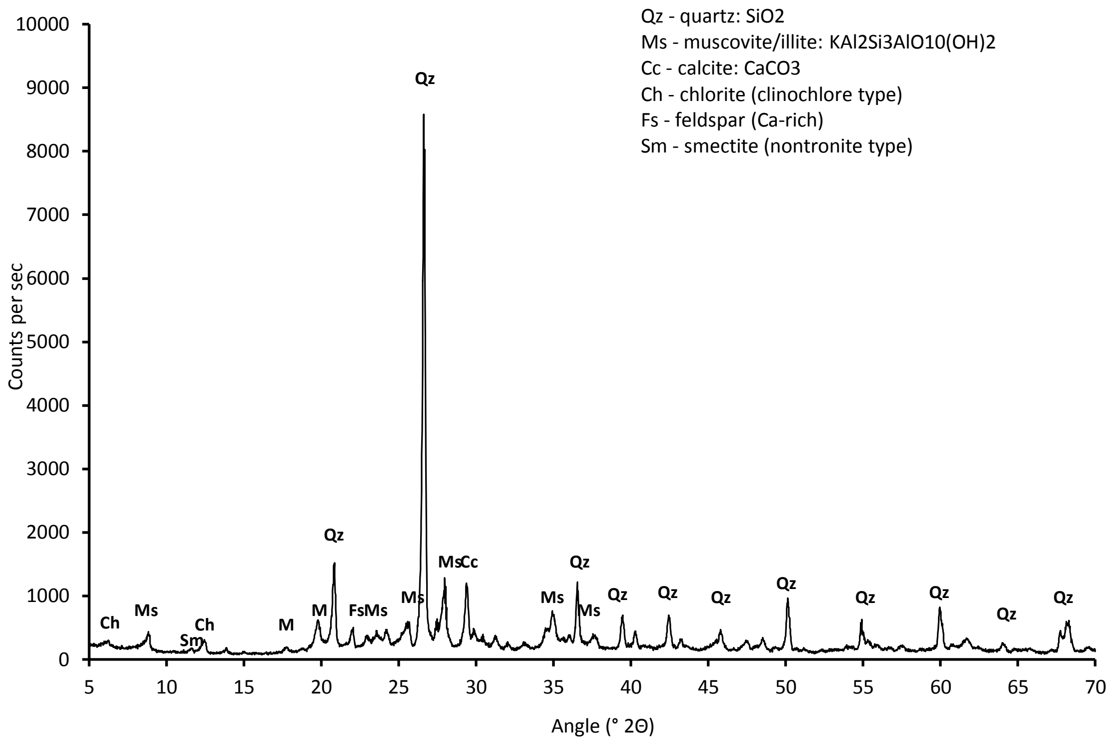


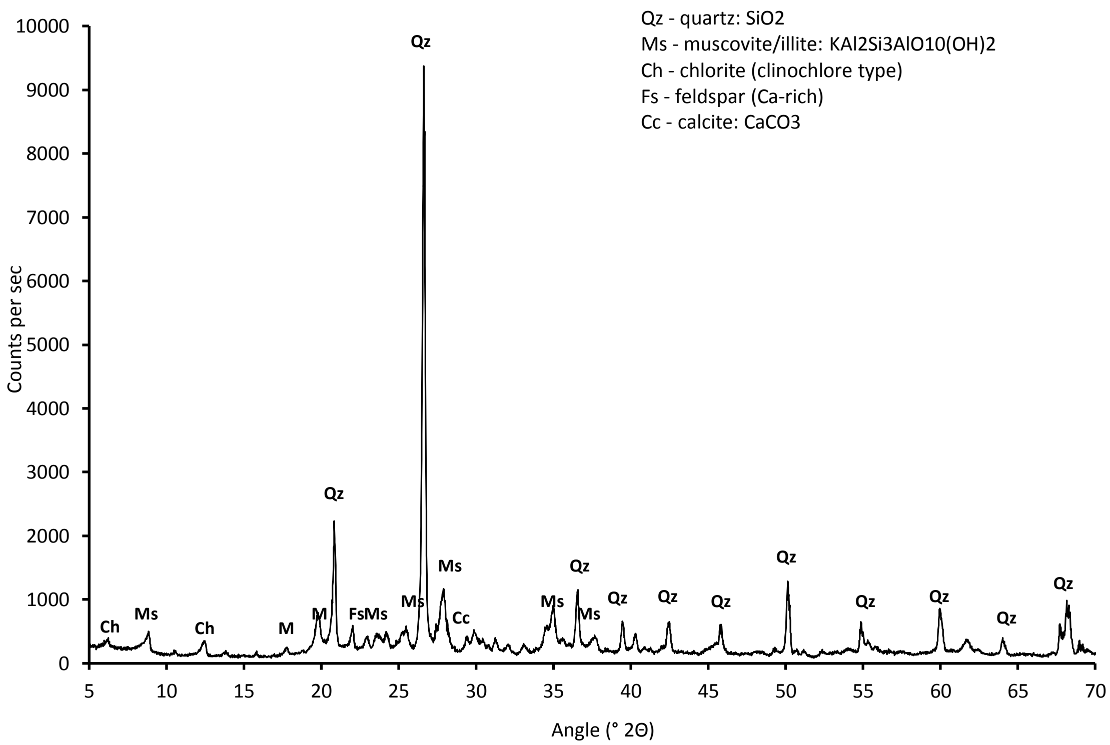


Fig. 9.1. XRD peaks for bulk samples obtained from five locations within the west room of Cottown Schoolhouse.

9.3 Portable X-ray fluorescence spectroscopy (pXRF)

Laboratory-based XRF spectroscopy has been employed in geoarchaeological assessments since the 1960s (Hall, 1960), but the more recent development of handheld pXRF analysers has provided a watershed in facilitating the non-intrusive and rapid gathering of data from materials of cultural heritage significance (Liritzis and Zacharias, 2011). Portable instruments allow for the almost instantaneous *in situ* identification of chemical elements, including their abundance, and pXRF was used to acquire data from the internal surface of the west gable wall of Cottown Schoolhouse following a flooding event in February 2011. Using a Niton XL3t GOLDD+ XRF analyser (Thermo Fisher Scientific Inc., Waltham, MA, USA) on a vertical transect at two locations approximately 50 cm apart, *in situ* measurements of elemental concentrations could be taken across the lower, damp part of the mudwall to the upper, drier part of the mudwall. The instrument was operated with a helium purge to increase sensitivity to lighter elements and elemental concentrations were calculated using a theoretical calibration derived from a geological (Cu/Zn mineral series) matrix. The boundary between wet and dry areas on the wall was measured at ~35 cm above floor level which, interestingly, is consistent with the extent to which damp was noted to have risen in 1999 (Reen, 1999).

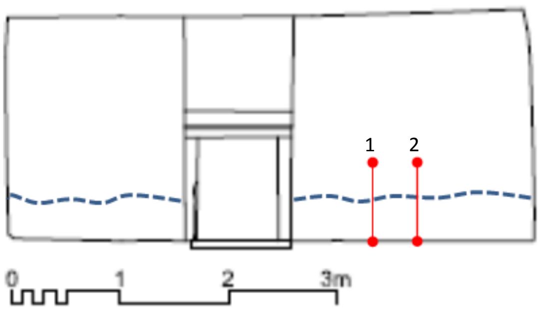
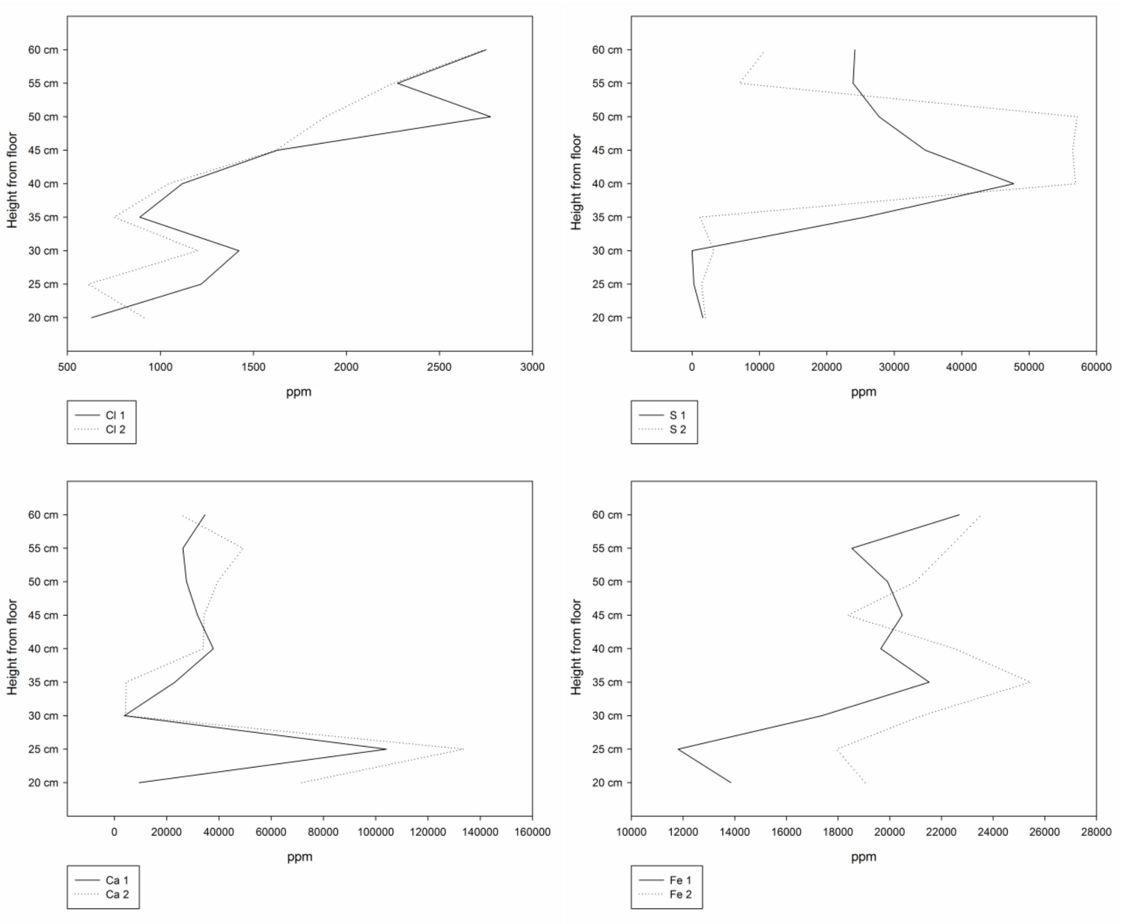


Fig. 9.2. Location of wet/dry boundary and positions of the vertical transects from where XRF measurements were taken on the internal surface of the west gable wall.

The elements that showed elevated concentrations at the surface of the wall included Cl, S, Ca, Fe, Si, Al, Mn and Ti. Plotting the results revealed a general trend in both locations for Cl increasing in abundance with wall height, but with a notable decrease at the boundary point. Sulphur was virtually absent at the wall surface in the damp area at both locations but extremely prominent at the wet-dry interface before falling again with increased height. It should be noted that although the maximum abundance of Cl was less than 3000 ppm, S rose to almost 50000 ppm in location 1 and almost 60000 ppm in location 2. Calcium spiked greatly within the damp area at both locations, reaching over 100000 ppm in location 1 and over 130000 ppm in location 2 before falling to negligible levels at the boundary point and rising thereafter to more consistent levels between 20000 and 50000 ppm.



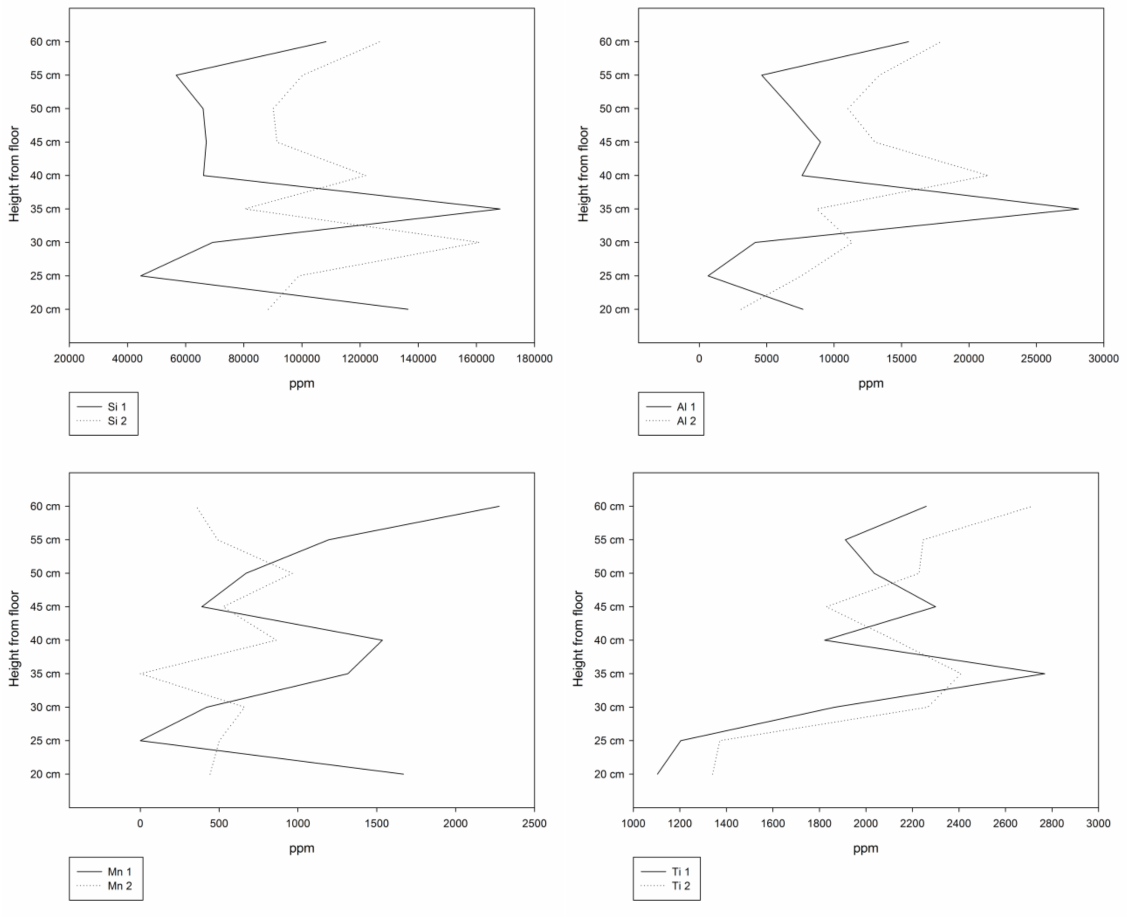


Fig. 9.3. Variable concentrations of chemical elements identified using XRF along two vertical transects at the internal surface of the west gable wall at Cottown Schoolhouse.

The relationship between the wet and dry areas of the wall and relative presence of certain elements suggest that soluble salts are transported through the mudwalls from ground level and occur variably at the surface. These variable surface concentrations would be explained by their transport at depth as a result of the capillary rise of groundwater. Salt efflorescence, crystallisation and hydration are widely recognised as key decay mechanisms in historic masonry structures, with the deterioration and flaking of stonework resulting from these processes at the surface. Climatic changes have stimulated a reappraisal of such explanations in work at Queens University Belfast, with Smith *et al.* (2011) having commented on notions of increased surface 'greening' and 'deep wetting' and the implications of these for salts-related decay of sandstone as a result of projected climate changes. They argue that prolonged periods of winter wetness will result in greater amounts of moisture at depth within building stone, with the corollary that soluble salts will penetrate correspondingly through ionic diffusion. Furthermore, wetting-drying cycles at the surface of materials, which can be as regular as intra-daily and have typically been the focus of sandstone decay research, will be lessened by the process of greening but with increased likelihood that salt reservoirs held at depth will contribute to surface decay when moisture leaches towards the surface from within.

9.4. Near infrared spectroscopy (NIR)

Like pXRF, NIR offers opportunities to gain rapid, non-intrusive information relating to the characteristics of historic building materials *in situ*. NIR was therefore employed as a further means of comparatively assessing the materials from Cottown Schoolhouse, using the post-treatment experimental blocks as reference materials in order to determine whether the technique can be used to characterise climate induced changes in a relatively complex material matrix (Parkin et al, 2013). Using a LabSpec 5000 FR Spectrometer (ASD Inc., Boulder, CO, USA), initial results indicated that the technique can be used to distinguish between clay types and also between samples of pure clay and clay mixed with aggregates. NIR was not able to demonstrate significant differences between experimental samples depending upon the controlled environment regimes they were subjected to, but with further exploration it may yet be the case that more serious weather damage can be quantitatively assessed by this method. NIR was, however, clearly able to distinguish between samples based on relative clay content and thus demonstrates potential as a further means of investigating the nature of historic earth buildings without removing material samples.

9.5 Conclusion

Of particular importance to the identification of appropriate repair materials for a structure such as Cottown Schoolhouse is an understanding of the mineraological composition of the original building materials used to raise the mud walls. The results indicate some minor differences between the samples, which were all taken from original sections of mud wall, and therefore reflect the heterogeneity of earth-based building materials even at the intra-site level. This in turn has potential implications for performance across different areas of the structure, which may vary depending on the location and depth that material was dug out from the ground at each point in a multi-phase construction process.

The pXRF data acquired at the Schoolhouse provide food for thought in relation to water uptake and internal surface deterioration in mass earth buildings. It is apparent from MMS sampling that areas of the north and west walls retained moisture at depth from November through to March. Combined with the pXRF data these clearly suggest a link between water uptake (and therefore wetness within the mudwalls at depth) and the variable surface prevalence of elements found in soluble salts. Further to this, it is interesting to note that in these surface materials concentrations of S were so much greater than Cl where the two elements occurred, thus adding credence to the notion that Na_2SO_4 should be considered ahead of NaCl as a widespread and potentially damaging soluble salt. NIR has the potential to offer further characterisation insights and can also be used *in situ* with portable models in conjunction with pXRF.

10. Micromorphological and micromorphometric analyses of field samples and experimental materials

10.1 Introduction

Geoarchaeological techniques have been used in limited but varied archaeological contexts to characterise the complexities of historic earthen architectures. Of greatest similarity to the approaches used in this research is the work of Friesem *et al.* (2011), who have sought to develop a model for micro-scale processes of mud brick deterioration through integrated geoarchaeological analysis of an abandoned house used as a case study in southern Israel (Fig. 10.1). Macro-scale site observation, archaeological excavation and materials' characterisation through XRF and Fourier transform infrared spectroscopy (FTIR) were used to contextualise micromorphological assessments, which provided the basis to develop a model of microscale deterioration whereby processes of erosion act differentially upon the fine fraction, coarse fraction and organic components.

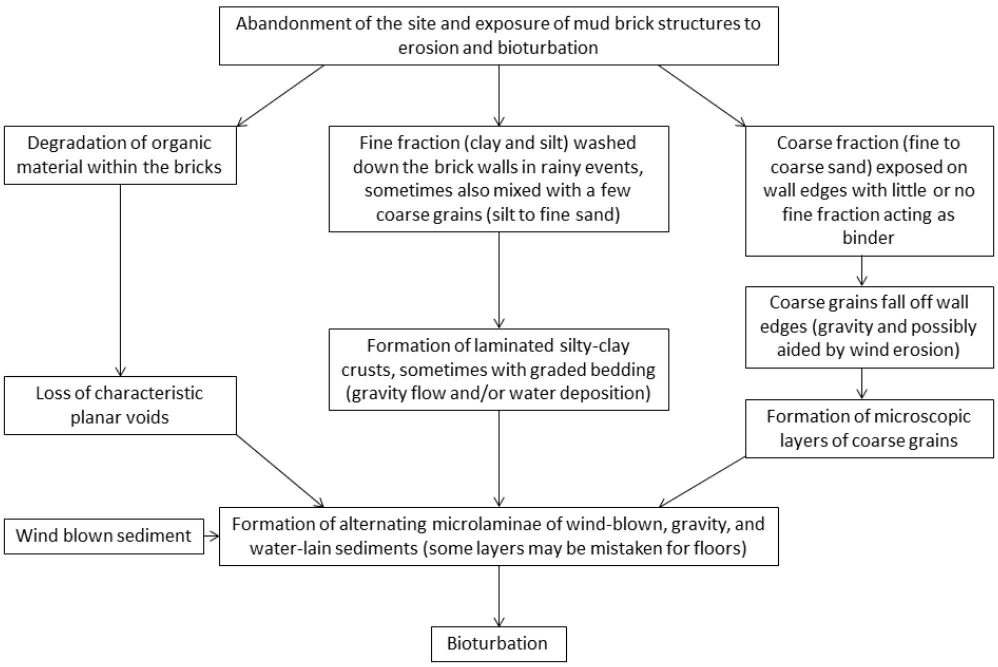


Fig. 10.1. Geoarchaeological model of micro-scale deterioration of mud brick walls in an arid environment. After Friesem *et al.* (2011), 'Degradation of mud brick houses in an arid environment: a geoarchaeological model'.

In the Scottish context, assessment of thin sections taken from Blackhouse 39 at Arnol on Lewis showed that the walls were erected with raw, stripped turf local to the site without any form of additional admixture (Holden *et al.*, 1998). In Belgium, micromorphological studies of the early-medieval Motte of Werken, which developed in the ninth and tenth centuries, examined methods of construction and pedogenetic processes related to water stagnation within the motte in the period since formation (Gebhardt and Langohr, 1999). Goodman-Elgar (2008) has provided a detailed geoarchaeological study of structural materials from abandoned pre-Columbian adobe dwellings in the Bolivian Andes, which attempts to align stages of wall deterioration outlined by McIntosh (1974) in relation to West African examples with these Bolivian settlements. Native American mounds dating to between 3600 and 400 years BP in the Mississippi River basin have been assessed using micromorphology to aid understandings of the materials used (including clay-rich soil blocks akin to adobe) and architectural, engineering and cultural complexities involved in their construction (Sherwood and Kidder, 2010). In Uruguay, large multi-period mound complexes comprised of functionally diverse earthen buildings developed over hundreds or even thousands of years from around 5000 years BP. The materials comprising these mounds appear homogenous and similar to natural soils. Micromorphological assessments have been used to develop understandings of the materials used in construction, episodes of renewed mound-building and spatially-differentiated functional areas (Villagran and Gianotti, 2012). In spite of the insights provided by such studies, however, there is a distinct contrast between the extant walls considered in this thesis, which have been subject to maintenance over the course of a relatively short history, and buried mounds with mixed soils that have been excavated centuries or millennia since original construction or abandoned adobe dwellings in arid environments. Thus, the absence of established protocols for describing and interpreting building materials originating from natural soils provides difficulties in terms of making comparisons across contexts, although this does afford the freedom to develop assessments appropriate to specific contexts.

10.2 Field samples

10.2.1 Micromorphology

The procedures outlined here in relation to the analysis of sampled materials were replicated in the analysis of experimental materials (10.3), as part of the wider discussion.

10.2.1.1 Sampling

For micromorphological and image analyses, samples of exposed mudwall material approximately 80*60*40 mm in size were extracted from the central dividing wall of the Old Schoolhouse (the main eastern wall in its original square-plan layout). The first sampling location was to the south side of the central fireplace at a height of around 50 cm and the second was directly above this from within the attic space. This provided a means of comparison between the lower part of the mudwall, which suffers from periodic winter flooding, and the upper part, which can be assumed to have remained relatively dry throughout the history of the building. Samples were obtained for comparative analysis from the Flatfield and Leetown sites. Two samples were taken from the exposed head of the west gable wall of the one-and-a-half storey barn at Flatfield Steading, one from the external edge and the other from the internal edge. One sample was obtained from the saturated remnants of the brick-faced mud walls of the derelict Leetown Victory Social Club. Two further samples were also taken from an experimental mudwall built in 1996 in Fort George as part of long-term experimental monitoring of traditional earth building materials' performance (Morton, 2004) (Fig. 10.2). This wall, topped with tiles for protection, was built using clay from the now disused brickworks at Errol, in the Carse of Gowrie, together with amendments of straw and aggregate. It was rendered with lime at its western end and left non-rendered at its eastern end, with one sample taken from each end.

Fig. 10.2. Experimental mudwall at Fort George, photographed in 2012, built using Errol clay with render applied to the left side as viewed. (Photo credit: D McLaughlin).

10.2.1.2 Sample preparation

Thin sections were prepared from the samples taken from Cottown, Flatfield, Leetown, Fort George and the experimental blocks at the Thin Section Micromorphology Laboratory, University of Stirling. Where necessary the samples were dried using vapour-phase exchange of acetone and subsequently cast in polyester resin (‘Glass Clear’ Polyester, ABL Stevens Ltd., Sandbach UK) before thin sections were manufactured from the blocks. The standardised manufacturing procedure is detailed online (http://www.thin.stir.ac.uk). Once resin impregnated, the samples were sliced and bonded to a glass slide. Soil thin sections would then be precision lapped to ~30 µm thickness, although it was not possible to do this mechanically for all slides because of the high clay content and heterogeneity of the samples. This meant that some hand-lapping was required, producing slightly more variation in slide thickness than would normally be desirable. It should also be noted that the process of thin section manufacture creates unavoidable artefacts which must be acknowledged during subsequent study. Clay domains can be prone to loss and shrinking and cracking can also be introduced during production as a result of water removal and resin impregnation (Adderley *et al.*, 2001).

10.2.1.3 Observations, results and interpretation

Thin section observations were made using an Olympus BX-50 petrological microscope (Olympus Corporation, Tokyo, Japan) and based on protocols established in the *International Handbook for Thin Section Description* (Bullock *et al.*, 1985) and the most recent procedures of Stoops (2003). Descriptions of structure, later augmented through the use of image analysis, and pedofeatures related to clay translocation and water transport were deemed to be most useful in facilitating the interpretation of processes involved in mudwall deterioration.

Macro-scale observations of the thin sections were made prior to micromorphological assessment and the relative heterogeneity of those manufactured from the Schoolhouse, Leetown and Fort George samples, in terms of randomly dispersed distinct mineral or fine-material rich regions, was noticeable in comparison with those manufactured from the Flatfield samples, which appear far more uniform. Larger organic, mineral and clay inclusions up to ~6 mm in diameter were also apparent in the Schoolhouse, Leetown and Fort George thin sections, but the Flatfield sections were devoid of such inclusions.

As with traditional applications of micromorphology in soil science, it is important to be aware of whether features present in the thin sections of sampled materials were inherited prior to erection or formed and developed *in situ* and an important point of qualification for the interpretation of materials extracted from earth buildings is that the ‘anthrosols’ used for construction are necessarily based on existing, naturally deposited soils. Therefore, care must be taken when inferring relative chronologies to the processes identified within the samples, especially if one considers the mixing and laying process involved in building a mudwall structure, with wet material being left to dry *in situ* following an artificial process of turbation, layering and compaction. This therefore emphasises the importance of using image analyses alongside micromorphological interpretations.

The identification of features indicative of deterioration related to water infiltration and associated shrink-swell and freeze-thaw processes is of primary concern to this thesis. It is also important to note that, unlike in typical soil or archaeological contexts, the materials studied here had rested above ground and were subject to water infiltration primarily as a consequence of water movement from below (although the walls of the derelict Leetown Victory Social Club suffered from direct rain water infiltration).

Microscopic observations indicated that the Schoolhouse, Leetown and Fort George samples exhibited vughy/blocky microstructures typified by vughs and frequent partially accommodated planes. The Flatfield samples both exhibited essentially massive microstructures with very few planes and vughs. Straw fragments were present in all samples, alongside other minimal organic inclusions such as wood fragments (Schoolhouse, Flatfield and Leetown sections) and plant tissues (absent from the Flatfield sections). The relative absence of pore pseudo morphs in the sections, which are known to result from the decomposition of straw and other organics in earth building materials (Macphail and Goldberg, 2010) indicates that the binding material remained intact at depth throughout the lives of the structures. Trace to rare occurrences of clay infillings and/or coatings were observed in the Schoolhouse Lower and Leetown sections in particular. All of the thin sections exhibited Fe/Mn oxide matrix impregnations and nodules to varying degrees.

It is likely that the microstructures of the sections are indicative of differences in construction process and levels of material deterioration at Flatfield when compared to the other sites. Indeed, the density of the material and close arrangement of coarse material would seem to correspond with the notion that the walls at Flatfield were erected with shuttering and subjected to higher levels of compaction that the more typical examples of mudwall material. The prevalence of accommodating planes in the Cottown, Leetown and Fort George sections indicates the dissociation of material as a consequence of shrink-swell processes. Furthermore, the evidence for clay translocation seen in the same sections, which is demonstrated by infillings and cappings in and around pores (Fig. 10.3), adds to the picture of dynamic materials subject to high levels of water movement (Kühn, Aguilar and Miedema, 2010), as well as freeze-thaw processes (Van Vliet-Lanoë, 2010).It therefore seems telling that these features are absent from both Flatfield sections. It is also worth noting the presence of areas of granular microstructure in the Cottown lower section, as this has been associated with the upper part of clay-rich soils subject to repeated freeze-thaw cycles (Van Vliet-Lanoë, 2010).

Redoximorphic features are indicative of the periodic saturation and desaturation of soils (Lindbo, Stolt and Vepraskas, 2010), with the cyclical reduction and oxidation of Fe/Mn typically manifesting as nodules, coatings and groundmass impregnations. It is difficult to identify, however, whether such features when identified in thin sections made from earth buildings' samples are necessarily a product of *in situ* weathering or inherited. It may be likely that such features found surrounding vughs or planes developed in the post-erection period, as the pores themselves most likely post-date the point at which mixing took place. Gerhardt and Langohr (1999) described post-depositional migrations of clay and Fe/Mn accumulations in sections relating to the upper part of the Motte of Werken, which they attribute to the migration and stagnation of water resulting in reduced conditions. Furthermore, banded impregnations are likely to be indicative of water movement through the materials post-erection as these are structured features. It is interesting to note the presence of these features quite prominently within the Flatfield sections, which do not exhibit signs of structural stress, and it may be that this reflects the impacts of the impermeable cement render applied to the walls in the 1970s. This layer has prevented the usual process of surface evaporation that is allowed by the use of "breathable" lime harl or limewash and may therefore have resulted in trapped water moving within the wall fabric without means of escape as vapour.

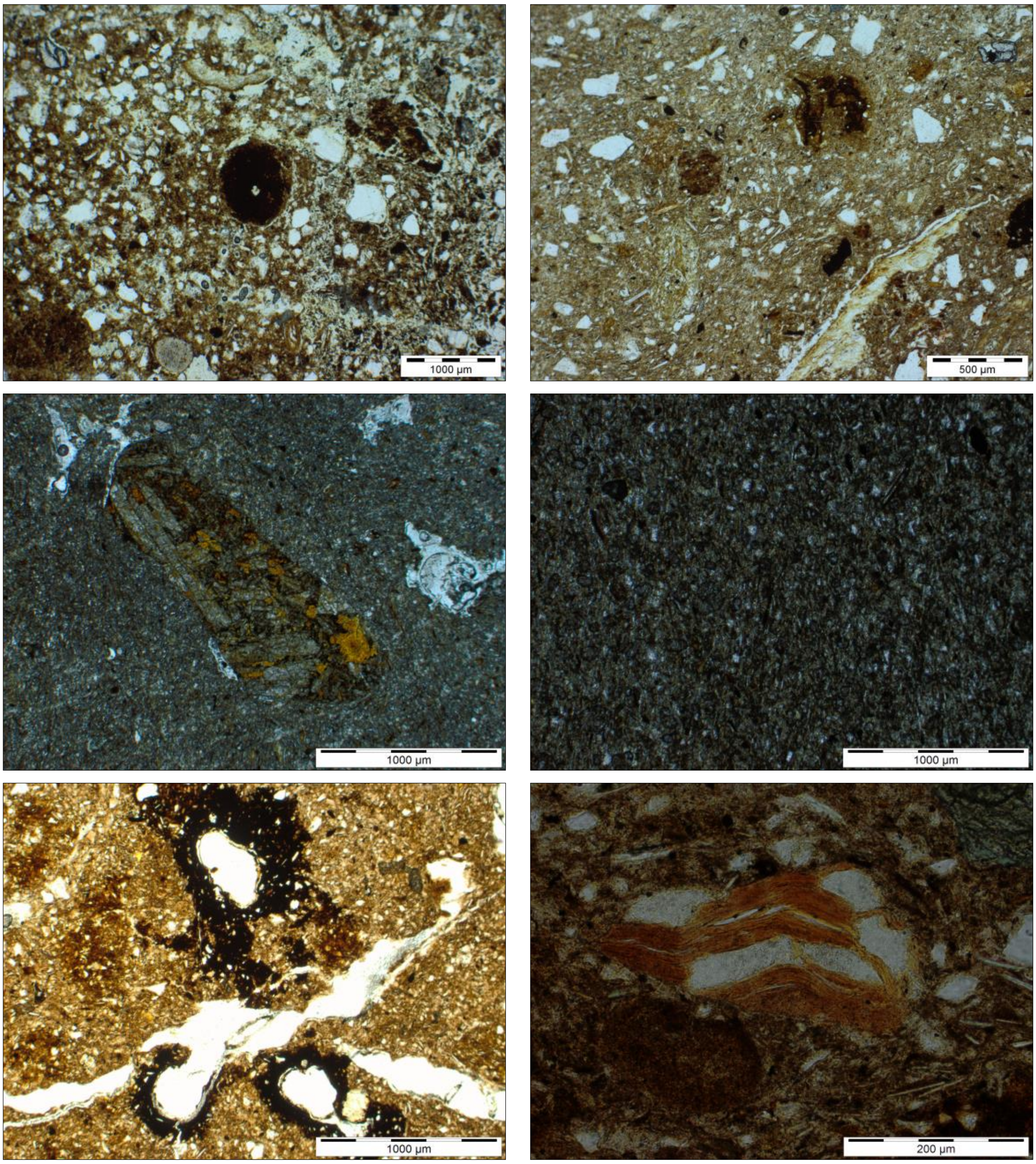


Fig. 10.3. Photomicrographs of field thin sections (all PPL). Top left: Cottown Lower. Fe/Mn nucleic nodule, with straw fragment above and crumb microstructure to the right of the image. Top right: Cottown Upper. Irregular matrix impregnations of Fe/Mn; planar void running along the length of straw fragment. Middle left: Flatfield External. Heavily weathered mineral fragment with clay infillings; irregular vughs within an otherwise massive microstructure. Middle right: Flatfield Internal. Typical massive microstructure. Bottom left: Leetown. Vughs with Fe/Mn hypocoatings around the edges. Bottom right: Leetown. Laminated clay infilling.

Table 10.1. Summary table of micromorphological observations of thin sections derived from field samples.

Thin Section	Structure			Groundmass											Pedofeatures			
				Coarse Mineral Material (>63µm)				Fine Mineral Material (<63µm)			Coarse Organic Material (>63µm)				Clay		Fe/Mn oxide	
	Microstructure	Accommodating planes	Vughs	Quartz/Feldspar	Muscovite / Biotite / Horn	Granite / Gneiss / Pegmatite	Phytoliths	Nature of fine mineral material (PPL)	Groundmass b Fabric (XPL)	C/f distribution pattern	Charcoal	Straw	Wood fragments	Plant tissue	Infillings	Coatings / hypocoatings / capping	Matrix impregnation / coatings / hypocoatings	Nodules
Cottown Lower	Crumb / Vughy/ Subangular blocky	***	****	****	t			Reddish brown	Stipple-speckled/ random striated	Close to single spaced porphyric	*	**	t	t	t	#	##	##
Cottown Upper	Vughy/ Platy	***	**	****	t			Reddish brown	Stipple-speckled/ random striated	Close to single spaced porphyric	*	**	t	t		t	#	#
Flatfield external	Massive	*	*	****	t			Greyish brown	Stipple-speckled	Close porphyric		*	t		t		###	##
Flatfield internal	Massive	*	*	****	t			Greyish brown	Stipple-speckled	Close porphyric		*	t				##	##
Leetown	Vughy/ Subang. blocky	***	**	***	t	*	*	Brown	Stipple-speckled/ random striated	Double spaced porphyric	*	**	*	t	#	#	###	##
Fort George Wall 5 Rendered	Vughy/ Subangular blocky	***	**	**		**		Reddish brown	Stipple-speckled/ random striated	Close to single spaced porphyric		*		t	t		#	##
Fort George Wall 5 Non-rendered	Vughy/ Subangular blocky	***	**	**		**		Reddish brown	Stipple-speckled/ random striated	Close to single spaced porphyric		*		t	t		#	##

Frequency class refers to the appropriate area of section

t = trace (<1%) * = very few (1 - 5%) ** = few (5 - 15%) *** = frequent (15 - 30%) **** = very frequent (30 - 50%) ***** = dominant (>50%)

Frequency class for pedofeatures

t = trace (<1%) # = rare (1 - 2%) ## = occasional (2 - 5%) ### = many (5 - 10%)

10.2.2 Image analysis

It was deemed unsuitable to mosaic across full thin sections, a technique that has been successfully developed and applied by Adderley *et al.* (2002). This was because areas of clay-rich or organic material were occasionally lost from some of the thin sections during processing, meaning that some areas of apparently extreme porosity are in fact artificial and had to be avoided during analysis. VandenBygaart and Protz (1999) have discussed issues of representivity in relation to quantitative studies of soil thin sections and developed standard protocols for the image analysis of soil subsamples. The procedures used here are also influenced by the practicalities of ensuring consistency in process across a large number of thin sections of variable quality from both field and experimental sources. Given this, the identification of multiple subsamples from within each section was deemed an appropriate approach to achieving representivity. This was vindicated through post-analysis statistical testing (10.2.2.4; Table 10.3), which indicated consistency between the sections based on assessments of subsample variations.

10.2.2.1 Methods

Images were acquired from across the thin sections using a CCD-based Olympus XC50 digital microscope camera attached to a trinocular Olympus BX51 polarizing microscope (Olympus Corporation, Tokyo, Japan) via an extension tube. Digital images were captured using AnalySIS Pro software, (Olympus Soft-Imaging System GmbH, Münster, Germany) at a nominal magnification of 40X using an apochromatic 2X magnification fluorite objective.

Processing and analysis of the thin sections followed prescribed procedures to ensure consistency (Appendix 5). The microscope was set at 2X magnification, with the voltage applied to the light source fixed and neutral density and LBD (light balancing daylight) filters adjusted to ensure an appropriate greyscale level. One of the neutral density filters was then removed and circularly polarised illumination applied using two orthogonal crossed polars (XPL) and two orthogonal ¼-wave plates inserted into the light path. This overcame issues stemming from the misidentification of minerals as pore space during attempts at binarisation. Eight images were acquired randomly from across each thin section, within the areas that exhibited original structural integrity, and for each of these the clear pore spaces were thresholded using hue/saturation/intensity values. Images were saved as TIFF files. It should also be noted that small particles were inevitably identified as pore space, therefore meaning that the original data contains small-scale artefacts. It was intended that the potential misidentification of particles would be overcome by using blue dye in the resin during impregnation of samples, but unfortunately this proved unsuccessful as the resin failed to cure when it was combined with the pigmented substance. Adjacent pixel connectivity was chosen with the minimum particle size set at 30 µm and holes were filled to ensure the complete survey of each pore space. The presence of air bubbles in the thin sections and discolouration of some pore spaces, created during the production process, provided very few artefacts. This, together with slight variations in slide thickness, meant that hue/saturation/intensity thresholds had to be carefully adjusted for each slide. Adderley *et al.* (2002) have discussed some of the issues involved in processing images from thin sections of varying thickness based upon colour thresholding, noting the difficulties in drawing comparisons between sections of different thickness when identifying objects. As porosity was the target feature in this research, however, such issues were not so much of an obstacle as only clear space was being identified, albeit with some adjustment for the discolouration noted above.

It was decided to focus the analysis on quantifying pore shape factor, sphericity and elongation as a means of determining the typical nature of pore spaces within the samples. Feret diameters were recorded as a means of indicating the potential connectivity of the original material, with the notion that increased variability of Feret values reflects higher connectivity in three-dimensional space. The sizes of all pores were also recorded and used to calculate porosity for each of the thin sections. This suite of measurements was deemed an appropriate means of further investigating structural differences between the samples.

10.2.2.2 Definitions

Definitions of shape are greatly constrained by human language (Russ, 1999) and the names given to donate certain features during image analysis vary between both software packages and authors. This has implication for any comparisons made between the results of image analysis conducted on the thin sections using analySIS and those obtained using Fiji following XRCT scanning of samples from Cottown (10.2.3).It is imperative, therefore, that consistencies in definition between the shapes identified in each set of analyses are outlined here. The names for shape values used in analySIS are adopted here, with variations in these names between the software packages and Russ (1999), which operates as an independent control, noted and clarified through expression as equations.

10.2.2.2.1 Shape factor

Shape factor is alternatively referred to in ImageJ software as “Circ.” (circularity) and by Russ (1999) as Formfactor. The shape factor gives an indication of how smoothly circular a shape is on a scale from 0.0 to 1.0, whereby a lower value indicates a more elongated jagged shape. This makes the measurement more sensitive to perimeter curvature than sphericity and is defined using area and perimeter values as follows:

$$\text{Shape factor} = \frac{4\pi * area}{perimeter^2}$$

10.2.2.2.2 Sphericity

Sphericity is termed roundness in Fiji outputs, as well as by Russ (1999), and is an alternative to shape factor when considering how circular a shape is. Sphericity is more sensitive to elongation than shape factor and is defined as:

$$\text{Sphericity} = \frac{4*area}{\pi*\max diameter^2}$$

10.2.2.2.3 Elongation

Elongation, referred to in ImageJ and by Russ (1999) as aspect ratio, is given as 1.0 for a perfect circle or square, with values increasing with greater deformation. Elongation is defined as:

$$\text{Elongation} = \frac{particle\ length}{particle\ width}$$

10.2.2.2.4 Feret diameter

Feret diameters are defined as the distance between perpendicular and parallel tangents at opposing particle boundary edges. In analySIS 3.0 these are measured at 1° intervals, meaning that 360 measurements are used as the basis from which to determine the maximum and minimum Feret values for each particle.

10.2.2.3 Results

Statistical analysis techniques were used to assess whether the differences in shape values and porosity across the sampled materials were significant (10.2.2.4). Consideration of the summary results shown in Table 10.2, without recourse to statistical methods, is also informative, however. Perhaps most striking is the extreme variance in pore size within each section, as exhibited by the values for standard deviation. Of these, the smallest value is 10117 µm^2 (Flatfield Internal) and the greatest 33865 µm^2 (Cottown Lower). This highlights an integral problem with the positive skewness of the pore size element of the dataset, the aspect from which all other observations derive and a potentially key determinant of deterioration, which contains large numbers of small particle results and few extremely large results for each section.

Although it had been expected that the results would indicate a certain level of skewness as a consequence of the difficulties in identifying very small pores, concurrently omitting equivalently-sized mineral grains, the extent of this was not necessarily expected. To account for this, it was decided to conduct a secondary level of data filtration based on the minimum pore diameter required for water transport in soils. Following the principles set out by Jongerius (1957), which were subsequently developed by Brewer (1964) and Greenland (1977), and recently discussed in combination with these later contributions by Pagliai and Kutilek (2008), it was decided to omit all data points (or pores) with a maximum Feret diameter of less than 75 µm. This delineation of the results highlights the utility of Feret diameter measurements. Since pore diameters are considered on two separate axes (minimum Feret and maximum Feret), this filtration therefore avoids a blanket removal of data based on a mean pore diameter measurement. Macropores with diameters greater than 75 µm were termed macrovoids by Brewer (1964, 182), with delineations below this used to define mesopores (30-75 µm), micropores (5-30 µm), ultramicropores (0.1-5 µm) and cryptopores (<0.1 µm). Each level of pore diameter relates to a specific soil-water characteristic and, although Pagliai and Kutilek (2008) choose to follow Greenland (1977) in referring to “transmission pores” as greater than 50 µm, it was decided here to follow Jongerius (1957) and Brewer (1964) as Greenland’s (1977) work was conducted in the context of agricultural tillage impacts on soil structure. This eliminates consideration of water transport through capillary menisci in pores of smaller diameter, preferring to consider preferential flow phenomena. The idea of preferential flow was introduced by Lawes, Gilbert and Warington (1882), whose field drainage experiments highlighted two different types of water and solute movement in soils (which they termed preferential flow and matrix flow) depending on soil type. Preferential flow relates to the uneven and often rapid transport of water and solutes through porous media containing macropores (drying cracks, for example) of variable dimensions through which most of the movement occurs.

The results of this data transformation are extremely informative. The most striking initial outcome is the drastic reduction in total number of pores identified for each thin section (Fig. 10.4). Crucially, however, this change in the number of observations has a limited impact on the overall porosity values both within and between each thin section. This therefore justifies the approach taken on the basis that the great majority of genuine pore space identified during image analysis is still represented within the data (Fig. 10.5).

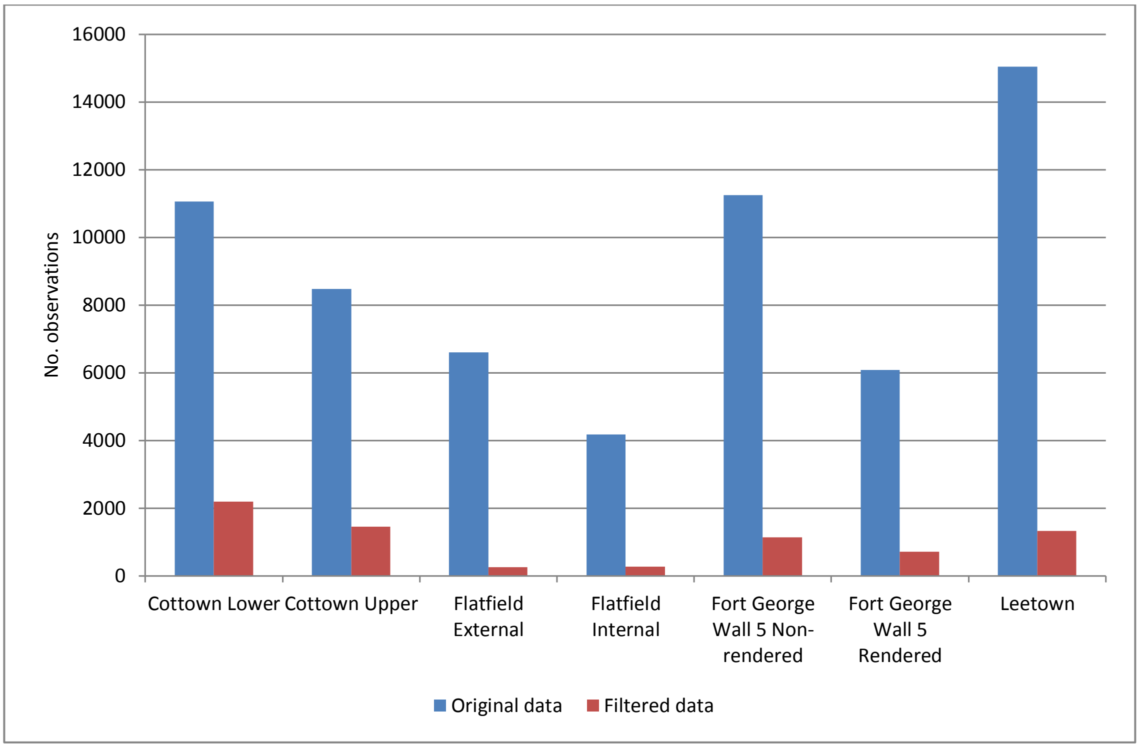


Fig. 10.4. Number of pore spaces identified in each thin section, showing original and filtered data.

The overall porosity values for each thin section demonstrate differences that may reflect the extent of material deterioration within each sample. Notably, the Cottown Lower section has a greater level of porosity than any other, whilst the Cottown Upper, Fort George

Non-Rendered and Leetown sections are grouped within a range of less than 1.3%. The rendered Fort George section sits between this group and the two Flatfield sections, which are much lower than all other samples. Within this, it may be worth noting that the Flatfield External section is more than twice as porous as the Flatfield Internal section, perhaps a function of moisture being trapped due to the impermeability of the external cement render, although the percentage difference is small in comparison to the remaining samples. The clear differences in the overall porosity values for the thin sections from Flatfield when compared with the others may reflect a combination of the differences in construction techniques between the sampled walls, as suggested in relation to the micromorphological descriptions, together with a relative absence of water ingress into the head of the wall at Flatfield. The rendered part of the experimental wall at Fort George appears less porous than its non-rendered equivalent and it is tempting to assign this to the added protection of the external surface and how this presumably limited water ingress in relation to the non-rendered portion of the wall.

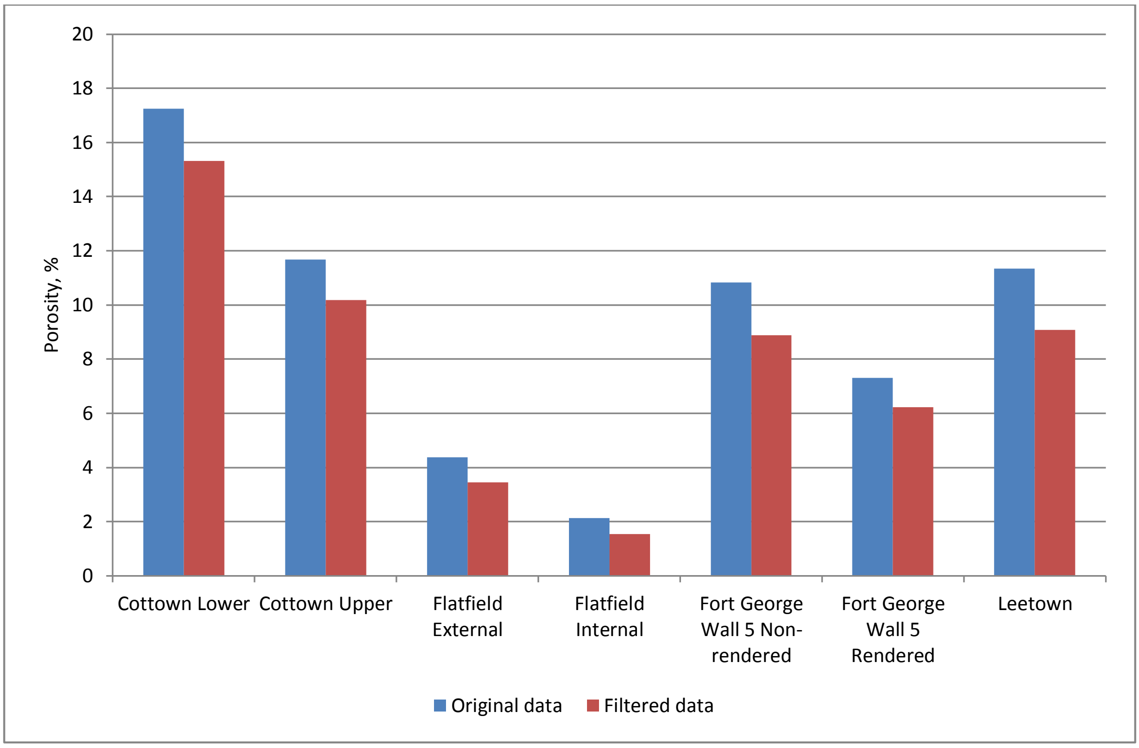


Fig. 10.5. Percentage porosity exhibited across the thin sections, showing original and filtered data.

Mean pore size values for the Cottown sections are near-identical, but overall porosity is notably different, therefore suggesting the development of similar pore spaces but with these having developed to a greater extent in the lower part of the wall. Pore spaces in the Flatfield sections are far less frequent, but when encountered in the section from towards the exterior of the wall they are extremely large in comparison to other sections. Aside from the value for the Flatfield External section, the mean pore size values are comparable across all sections, with those for the Fort George sections diverging the most. There is an inverse relationship between the mean particle sizes and overall porosity values recorded for the Fort George sections, with smaller mean pore size seen in the more porous non-rendered section. The Flatfield Internal and Leetown sections exhibit mean pore sizes close to those for the Cottown sections, yet overall porosity values are highly variable between these. It is worth noting that the overall porosity of the Leetown slide is extremely close to the upper Schoolhouse and non-rendered Fort George slides, indicating structural dissociation within the walling material. The walls at Leetown were faced with brick as a means of shuttering that, unlike at Flatfield, remained permanent. This might explain the intermediate nature of the Leetown material when set alongside the divergent Schoolhouse and Flatfield samples.

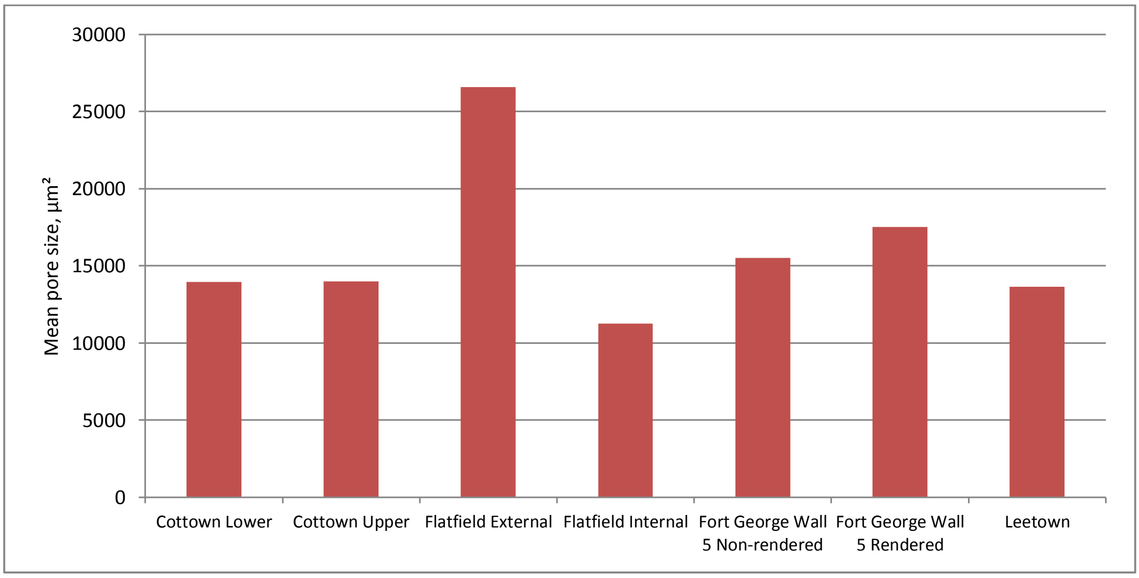


Fig. 10.6. Mean pore size values across the thin sections, based on filtered results.

The greatest mean of mean Feret diameter is seen in the Flatfield External section, followed by that exhibited in the Cottown Upper section. Conversely, the lowest mean of mean Feret diameter value is found in the Leetown section (Fig. 10.7). Mean pore size is distributed quite evenly, with exception to the Flatfield External section, and does not reflect overall porosity, which is much greater in the Schoolhouse Lower section than in any other. As previously discussed, the presence of water is essential to the process of ice separation in soil microstructures, with the effects variable depending upon depth and the length of frost periods. It has been suggested that pores in silty and loamy soils with mean diameters of ~50 µm, which sits within Brewer's (1964) definition of mesoporosity where water is stored but not transported, are ideal for ice nucleation (Van Vliet-Lanoë, Coutard and Pissart, 1984). The mean minimum Feret values after data filtration for all thin sections is upwards of 73 µm but it would seem noteworthy that the median results for these values come much closer to 50 µm, ranging between 48.67 µm (Flatfield External) and 62.66 µm (Cottown Upper). This therefore indicates an inherent likely susceptibility within the pore size distribution of these mass earth materials to water storage and subsequent ice separation.

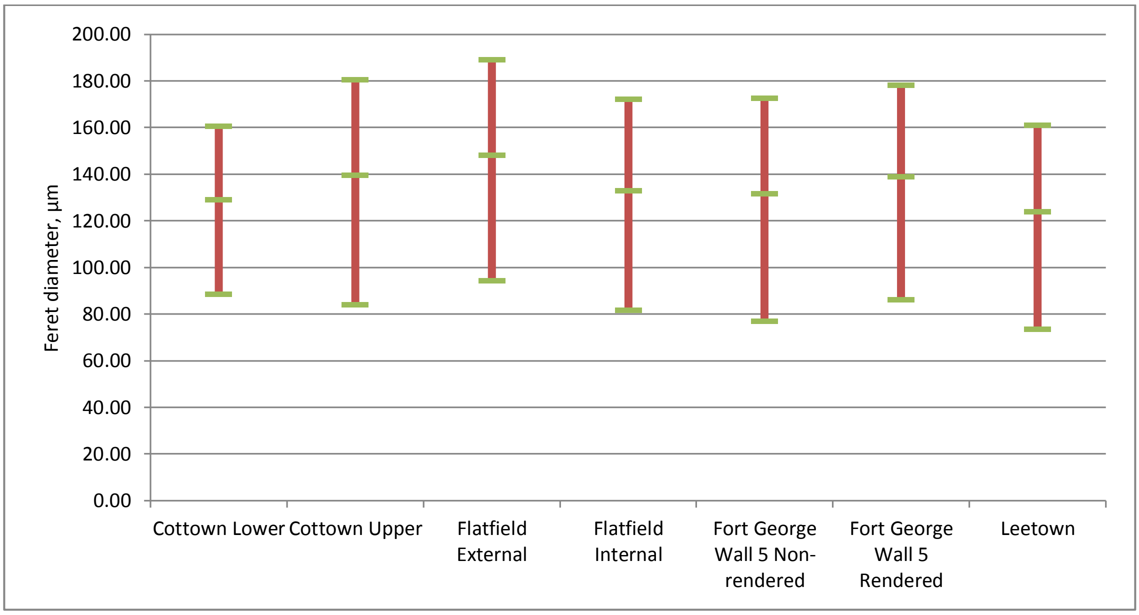


Fig. 10.7. Mean minimum, mean maximum and mean of mean Feret diameter values across the thin sections, based on filtered data results.

Table 10.2. Summary table of original and filtered image analysis data for thin sections derived from field samples.

			Shape						Connectivity						Porosity		
	Sample	Pores, n	Mean SF	Mean Sph.	Mean El.	SD SF	SD Sph.	SD El.	Mean min Feret dia. µm	Mean max Feret dia. µm	Mean of mean Feret dia. µm	SD min Feret dia. µm	SD max Feret dia. µm	SD mean Feret dia. µm	Mean pore size µm²	SD pore size µm²	% porosity
Original data	Cottown Lower	11051	0.35	0.31	2.19	0.17	0.19	0.95	34.84	62.72	50.57	55.81	100.21	79.72	3110	33865	17.3
	Cottown Upper	8474	0.44	0.3	2.33	0.2	0.2	1.25	31.21	61.58	48.55	50.77	108.15	82.72	2746	28700	11.7
	Flatfield External	6607	0.4	0.26	2.43	0.17	0.19	1.06	20.31	39.2	31.13	34.73	68.45	53.35	1316	27742	4.4
	Flatfield Internal	4172	0.4	0.24	2.58	0.18	0.18	1.15	21.58	43.8	34.3	31.69	60.19	46.83	1019	10117	2.1
	Fort George Wall 5 Non-rendered	11248	0.43	0.29	2.27	0.19	0.19	1.03	25.35	49.38	39.04	41.00	104.56	75.92	1918	33432	10.8
	Fort George Wall 5 rendered	6076	0.43	0.3	2.22	0.2	0.2	0.99	27.74	52.66	41.91	47.98	99.8	76.63	2392	30689	7.3
	Leetown	15042	0.29	0.28	2.35	0.13	0.19	1.15	24.36	47.37	37.46	33.14	82.46	61.48	1502	32271	11.3
Filtered data	Cottown Lower	2186	0.17	0.30	2.28	0.10	0.20	1.08	88.51	160.45	129.07	108.74	195.10	154.74	13964	75183	15.32
	Cottown Upper	1450	0.24	0.23	2.91	0.14	0.19	1.87	84.01	180.51	139.50	106.58	224.46	171.64	13981	68290	10.18
	Flatfield External	258	0.12	0.22	2.87	0.08	0.18	1.58	94.11	188.92	147.95	156.07	306.56	239.20	26583	138258	3.44
	Flatfield Internal	274	0.14	0.20	3.03	0.09	0.18	1.52	81.72	171.91	132.82	104.26	188.98	148.27	11243	38092	1.55
	Fort George Wall 5 Non-rendered	1141	0.17	0.23	2.90	0.11	0.19	1.73	76.90	172.37	131.57	114.36	299.18	215.45	15519	104019	8.89
	Fort George Wall 5 rendered	708	0.18	0.23	2.70	0.10	0.17	1.41	86.07	178.09	138.82	124.28	257.66	197.49	17531	88501	6.23
	Leetown	1325	0.11	0.23	2.96	0.06	0.19	1.86	73.40	161.03	123.78	96.25	248.00	183.98	13639	108021	9.07

*SF refers to shape factor; Sph. refers to sphericity; El. Refers to elongation.

10.2.2.4 Statistical analyses

Statistical testing of the data allows for the identification of where significant differences in the types of pore spaces within and between the samples may occur. The positive skewness of the data, however, meant that a suitable nonparametric method was required. Following the example of Siegel (1956), The Kruskal-Wallis One Way ANOVA by Ranks method (Minitab 14, Minitab, Coventry, United Kingdom) was used to test for differences in the results between all samples for shape factor, sphericity, elongation, minimum Feret diameter, maximum Feret diameter, mean Feret diameter and pore area. The resulting data was then tested using the Bonferroni *post hoc* method in Microsoft Excel 2010 (Microsoft Corporation, Redmond, WA, USA), in order to ascertain precisely where significant differences occurred (Table 10.4). This was achieved by individually testing for significant differences between pairs of data, with the confidence level for all results fixed at 95% (α=0.05), using the following inequality:

$$|\bar{R}_u - \bar{R}_v| \geq Z_{a/k(k-1)} \sqrt{\frac{N(N+1)}{12}\left(\frac{1}{n_u} + \frac{1}{n_v}\right)}$$

The results of these tests are summarised below (Table 10.3). It should be initially noted that no significant differences in subsample variation across the sections were observed, which corroborates the notion that the differences between the sections can be attributed to their overall characteristics rather than intrinsic heterogeneity. Shape factor is significantly different between almost all slides, whereas significant differences in sphericity and elongation are mainly observed in interactions involving the Cottown Lower section. This suggests that pore sphericity and elongation are more consistently developed across the materials, with the results demonstrating how these factors are closely related. The increased sensitivity of shape factor to pore roughness resulted in a greater return of significant differences. Minimum Feret diameter returned a greater number of significant differences between the sections than maximum and mean Feret diameter, again with all interactions involving the Cottown Lower sections being significant, which highlights the importance of recognising the variability of intra-pore diameter measurements.

It is interesting to note that although significant differences between the Cottown sections were observed for all factors but mean Feret diameter and pore size area, the other intra-site interactions returned only one significant difference based on the results for shape factor data from each Flatfield section. No significant differences were observed between the Fort George sections for any of the factors. It is therefore tempting to assign this pattern of results to the increased damage suffered in the lower part of the west gable wall of Cottown Schoolhouse. It may be that greater sphericity and lower elongation values for the Cottown Lower section when compared with the other sections reflect the greater predominance of vughs, which in turn may have developed within the original material as a consequence of the dissociative effects of the types of environmental pressures previously discussed.

Table. 10.3. Table of interactions between thin sections, indicating whether significant differences for each variable of interest were observed. Note that a list of abbreviation descriptions can be found on pages xi-xii.

		Shape Factor	Sphericity	Elongation	Min Feret	Max Feret	Mean Feret	Area
Sample interactions	CoLo-CoUp	/	/	/	/	/	X	X
	CoLo-FG5NR	X	/	/	/	X	/	/
	CoLo-FG5R	X	/	/	/	X	X	X
	CoLo-Flex	/	/	/	/	X	X	/
	CoLo-Flin	/	/	/	/	X	X	/
	CoLo-Lee	/	X	/	/	/	/	/
	CoUp-FG5NR	/	X	X	/	/	/	/
	CoUp-FG5R	/	X	X	X	X	X	X
	CoUp-Flex	/	X	X	X	X	/	/
	CoUp-Flin	/	X	X	/	X	X	/
	CoUp-Lee	/	X	X	/	/	/	/
	FG5NR-FG5R	X	X	X	X	X	X	X
	FG5NR-Flex	/	X	X	X	X	X	X
	FG5NR-Flin	/	X	X	X	X	X	X
	FG5NR-Lee	/	X	X	X	X	X	/
	FG5R-Flex	/	X	X	X	X	X	/
	FG5R-Flin	/	/	/	X	X	X	/
	FG5R-Lee	/	X	X	X	X	/	/
	Flex-Flin	/	X	X	X	X	X	X
	Flex-Lee	X	X	X	X	X	X	X
	Flin-Lee	/	X	X	X	X	X	X
Subsample interactions*		X	X	X	X	X	X	X

*Determined by whether >50% of all subsample interactions deliver significant results
"/" = statistically significant (α=0.05); "X" = not statistically significant.

Table 10.4. Non-parametric statistical analyses of shape factor: an example of outputs using Kruskal-Wallis One Way ANOVA by Ranks and Bonferroni post hoc methods.

Kruskal Wallis One Way ANOVA by Ranks for Shape Factor

Assumes 7 independent groups

Sample	N	Median	Ave	Z
CoLo	2186	0.15	3792	3.19
CoUp	1450	0.206	4815	22.94
FG5NR	1141	0.15	3696.3	0.44
FG5R	708	0.1626	3923.3	3.33
Flex	257	0.1103	2520.1	-8.86
Flin	274	0.1264	3103.7	-4.52
Lee	1325	0.1016	2403.4	-24.05
Overall	7341	3671		

H = 1009.26 DF = 6

P = <0.001

Results of Bonferroni *post hoc* test

	Diff in Ave Rank		LL	UL		Sample Sizes n1	n2		
CoLo-CoUp	-1023	218.04	-1241.040	-804.960	**Sig**	2186	1450	alpha	0.05
CoLo-FG5NR	95.7	235.12	-139.421	330.821		2186	1141	k	7
CoLo-FG5R	-131.3	278.38	-409.682	147.082		2186	708	N	7341
CoLo-Flex	1271.9	424.53	847.375	1696.425	**Sig**	2186	257	Alpha/(k*(k-1)	0.00119
CoLo-Flin	688.3	412.57	275.727	1100.873	**Sig**	2186	274	z(Alpha/(k*(k-1))	3.038074
CoLo-Lee	1388.6	224.14	1164.462	1612.738	**Sig**	2186	1325		
CoUp-FG5NR	1118.7	254.77	863.935	1373.465	**Sig**	1450	1141		
CoUp-FG5R	891.7	295.16	596.539	1186.861	**Sig**	1450	708		
CoUp-Flex	2294.9	435.71	1859.188	2730.612	**Sig**	1450	257		
CoUp-Flin	1711.3	424.08	1287.225	2135.375	**Sig**	1450	274		
CoUp-Lee	2411.6	244.67	2166.934	2656.266	**Sig**	1450	1325		
FG5NR-FG5R	-227	307.99	-534.994	80.994		1141	708		
FG5NR-Flex	1176.2	444.51	731.694	1620.706	**Sig**	1141	257		
FG5NR-Flin	592.6	433.11	159.495	1025.705	**Sig**	1141	274		
FG5NR-Lee	1292.9	260.00	1032.897	1552.903	**Sig**	1141	1325		
FG5R-Flex	1403.2	468.83	934.372	1872.028	**Sig**	708	257		
FG5R-Flin	819.6	458.03	361.566	1277.634	**Sig**	708	274		
FG5R-Lee	1519.9	299.69	1220.206	1819.594	**Sig**	708	1325		
Flex-Flin	-583.6	559.03	-1142.635	-24.565	**Sig**	257	274		
Flex-Lee	116.7	438.80	-322.095	555.495		257	1325		
Flin-Lee	700.3	427.24	273.058	1127.542	**Sig**	274	1325		

10.2.3 Micro X-ray computed tomography (μXRCT)

During the course of research an opportunity arose to explore the potential of μXRCT to offer novel insights into mudwall building materials, by making further use of the Schoolhouse samples extracted for micromorphological assessment. Adderley *et al.* (2001) recognised the potential utility of high resolution XRCT as an adjunct to the micromorphological and micromorphometric analyses of anthropogenically-derived archaeological soil deposits, noting the limitations inherent to the two-dimensional assessment of thin sections when attempting to explore relationships and processes within heterogeneous samples. μXRCT offers the opportunity to overcome the limitations of micromorphometric techniques by conducting fully quantitative assessments of undisturbed samples in three dimensions. Adderley *et al.* sought to use XRCT partly as a means of materials' characterisation, based on the relative densities observed in the digitally reconstructed samples. The approach taken here, however, was to explore porosity at varying depths within the samples. This meant that only differentiation between extant material and pore space was necessary and could be achieved through binarisation of the image slices representative of staged intervals through the material.

10.2.3.1 Method

The outward-facing offcuts from the resin-impregnated blocks were taken to the μSIMCT Laboratory in the SIMBIOS Centre at the University of Abertay, where they were scanned using a high resolution (5 μm) system and digital radiograms captured with a 160 keV X-ray source and 12 bit CCD Camera (X-Tek, Tring, UK). Image slices were then reconstructed using CT-Pro software (Nikon Metrology NV, Nikon, Tokyo, Japan). Although it would have been preferred to pursue this opportunity prior to the manufacture of thin sections, it was nonetheless important to consolidate the sampled material, through impregnation, prior to scanning. The success in scanning samples alleviated concerns as to impacts that the resin may have had on the outputs, although some beam hardening was observed on the edges of the images. Image stacks were produced for each sample at a voxel resolution of 30 µm. One unforeseen consequence of the scanning process was that the image stacks were generated on an angled plane, meaning that the samples had to be digitally reconstructed using the Volume Viewer plugin in the open-source Fiji image processing software package (Schindelin *et al*., 2012). This is itself an extension of the widely used ImageJ open source software originally developed for medical research purposes by the United States' National Institute for Health (Rasband, 1997-2014). Once reconstructed at the correct orientation, the digital renderings could be re-sliced in order to ascertain structural variability in three-dimensions

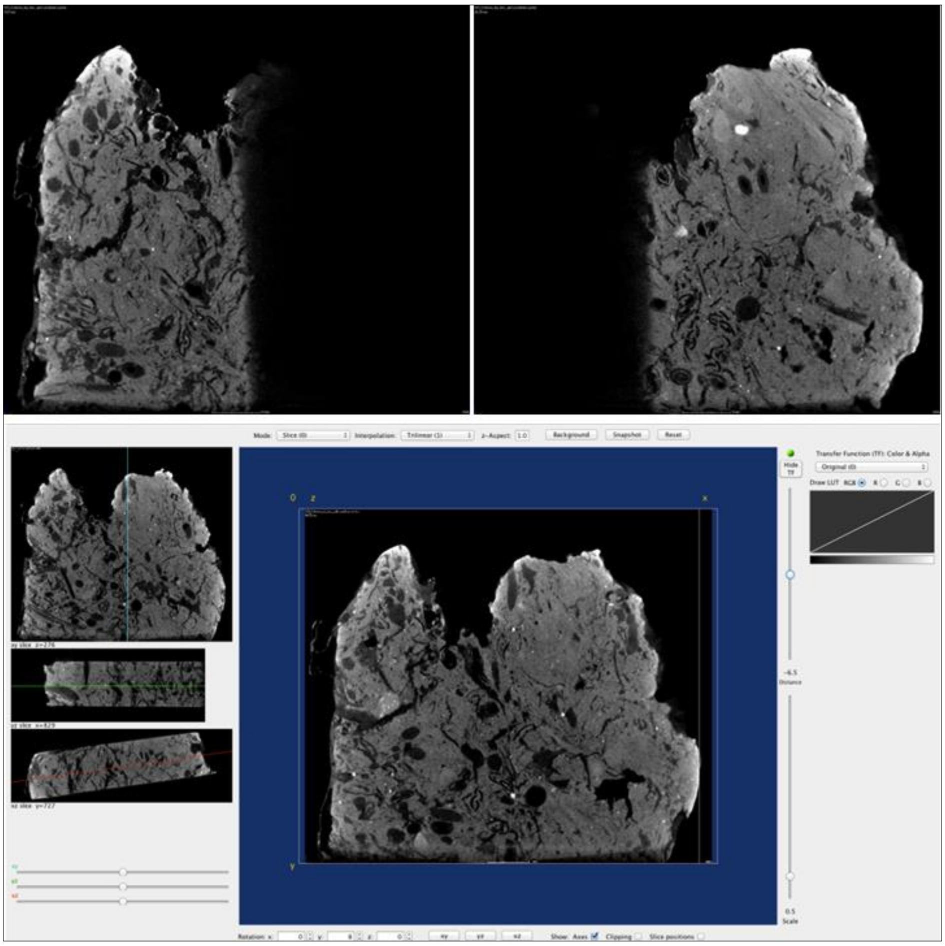


Fig. 10.8a. The stages used in the preparation of the raw XRCT scan slices. As noted, the orientation of the samples meant that slices were generated on an angled plane (see top row) through the scanned materials and therefore had to be manipulated before analysis could take place. Each set of images was initially uploaded in Fiji as a stack, which was then processed using the Volume Viewer plugin (second row) and realigned.

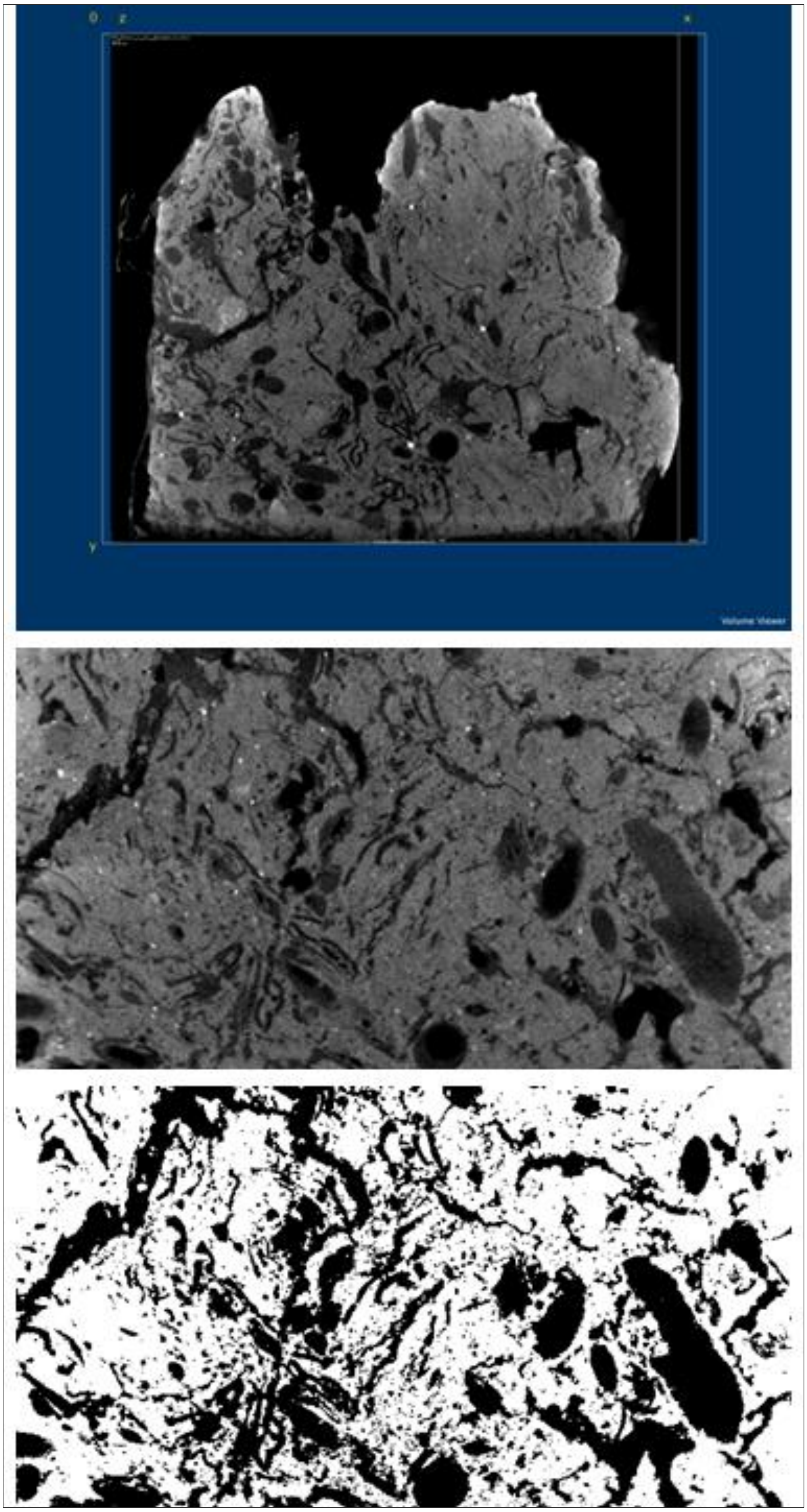


Fig. 10.8b. Once realigned and digitally consolidated into three-dimensional models, the material could be re-sliced on the required orientation to give a series of images of the material representing increasing depth within the sampled mudwall. These were then each cropped as a group so as to eliminate the space around each image and the effects of beam-hardening (row four). These subsamples were then binarised (bottom row), giving contrast between the hard mineral and pore space and organic content.

Using the Fiji toolbar the 0.3 mm-spaced image stacks rendered from the digital reconstructions of the samples were cropped to ensure that only the main body of the structures would be analysed, avoiding spaces around the edge of the images. These cropped images were then processed to produce binary images using the ImageJ IsoData method to transform each image in each stack. These were inverted in order to target the pore spaces for analysis, with the minimum particle size set at 30 μm^2, therefore repeating the criteria used in thin section image analyses prior to data filtration. For each slice from the two samples data were obtained for the particle count (with 'particle' referring to a discreet pore space), total porosity, mean particle area, percentage porosity, particle perimeter length, particle circularity and Feret diameter calculations.

10.2.3.2 Results

Aside from investigating the applicability of the technique, the primary focus of using XRCT was to gain insights into variations in porosity depending upon depth. The results of this are shown below (Fig. 10.9) and indicate that porosity values are noticeably variable within a relatively small depth range. The consistency of the difference in porosity values between the two samples is noteworthy, but, perhaps more interestingly, the results of the XRCT image analyses differ greatly from those based on thin sections of the same material (Table 10.5). Vast disparities are observed in the pore shape values, as well as the Feret, pore size and percentage porosity measurements. Furthermore, the reported porosity values indicate a greater mean pore space area in the Cottown Upper sample than in the Lower sample, the inverse of the relationship seen in the thin section results.

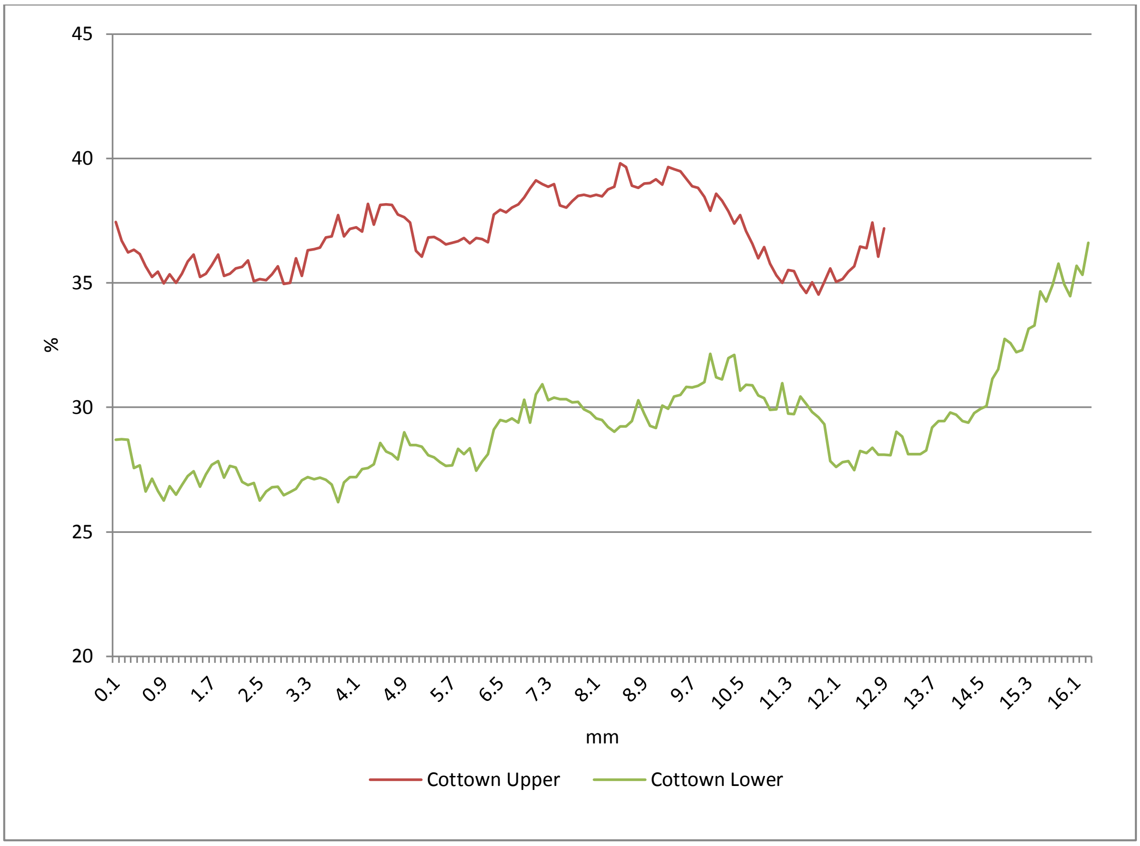


Fig. 10.9. Percentage porosity at varying depth within the resin impregnated Cottown Upper and Cottown Lower samples.

The disparities observed may be explained in a number of ways. Firstly, the samples subjected to XRCT scanning were from close to the surface of the wall, where the dry material was most friable and susceptible to fracturing during extraction, whereas the cohesiveness of the wet material was more easily retained. In discussing the results of the thin section image analyses, it was noted that one limitation was the unavoidable inclusion of some small mineral particles as artefacts in the attempts to quantify pore spaces, which therefore artificially reduces the Feret diameter and pore size values. In contrast, the XRCT image analyses inevitably included straw when quantifying pore spaces as the technique clearly identifies hard mineral material but not organic content, due to its lower density and the inconclusive grey values that are derived from this. This suggestion is corroborated by the shape value results for samples scanned using µXRCT, with the high shape factor and sphericity values representing very round and smooth pore spaces typified by straw in cross-section but not representative of the irregular pore spaces observed in thin section.

Table 10.5. Comparison of thin section image analysis and mean XRCT results across the image slices.

	Mean SF	Mean Sph.	Mean El.	SD SF	SD Sph.	SD El.	Mean of mean Feret dia. (µm)	SD of mean Feret dia. (µm)	Mean pore size (µm²)	SD pore size (µm²)	Mean % porosity
Thin Section Image Analysis											
Cottown Lower	0.17	0.30	2.28	0.10	0.20	1.08	129.07	154.74	13964	75183	15.32
Cottown Upper	0.24	0.23	2.91	0.14	0.19	1.87	139.50	171.64	13981	68290	10.18
µXRCT Slice Image Analysis											
Cottown Lower	0.87	0.72	1.64	0.23	0.79	0.79	211.5	529.1	53030	654478	29.25
Cottown Upper	0.88	0.74	1.60	0.22	0.79	0.79	163.7	533.7	53607	1148981	36.96

*SF = shape factor; Sph. = sphericity; El. = elongation.

It was determined to investigate whether the difficulties in differentiating between pore space and organic material in µXRCT scanning could be overcome if integrated approaches to structural characterisation are developed alongside thin section data. For example, if the mean porosity values for the µXRCT image slices include both pore space and organic material, these can be used to determine the mean amount of hard mineral material in each sample by simply subtracting the percentage porosity from the total area percentage. This gives hard mineral values of 70.75% for the Lower sample and 63.04% for the Upper sample. These values can then be used in conjunction with the more precisely determined porosity values obtained from the thin section image analyses to give estimates for the amount of hard mineral material, organic material and pore space in each sample. The results of this process are given below (Table 10.6).

Table 10.6. Calculations of percentage mineral content, organic content and pore space within the Cottown Schoolhouse samples, based on the integration of thin section image analysis and µXRCT image analysis data.

	Cottown Lower	Cottown Upper
Hard mineral, %	70.75	63.04
Organic, %	13.93	26.78
Pore space, %	15.32	10.18

In this example, however, the values remain questionable, as the thin section material was taken from slightly deeper within the sample than the surface offcuts scanned using µXRCT. Furthermore, the supposition that a quarter of the sampled material consisted of straw or other organic material is dubious and it would seem that the difficulty in making a distinction between organic material and pore space in the µXRCT-scanned materials remains an issue. Elyeznasni *et al*. (2012) have discussed problems encountered when trying to identify coarse organic matter in XRCT images of undisturbed soil samples, highlighting issues such as the varying stages of decomposition and the impacts of different combinations of material or water phases within pore spaces. The authors of this study proposed using micromorphology to make informed identification of coarse organic matter in XRCT scan outputs and it may be that this reversal in procedure could be applied with success in future in the context of earth buildings research.

Such high resolution X-ray computed tomography nevertheless presents an opportunity to gain structural insights that move beyond those provided through thin section analyses alone – not least because of the cost involved in the production of each thin section slide – and, critically, avoids any wastage of valuable extracted material. The experience gained from this process has allowed for recommendations as to an idealised model for sampling using the techniques outlined in relation to field sampling and these are elucidated in the concluding remarks (Chapter 11).

10.3 Experimental materials

10.3.1 Micromorphology

The procedures of sample preparation and micromorphological description for the thin sections processed from experimental materials follow the same as those outlined for the field samples discussed previously.

10.3.1.1 Method

Subsamples were taken from each of the experimental blocks described at the end of Chapter 6. These materials were taken from the lower part of the blocks where they interfaced with their plinths and were presumed to have experienced the greatest water/solute uptake. The delicate nature of the samples meant that they were cover slipped for protection, which unfortunately negated the use of XRF to further investigate the potential variability of elemental concentrations across the thin sections.

10.3.1.2 Observations

Macroscopically, the heterogeneity of the mixed composition sections is clearly visible in contrast to the homogeneity of those consisting purely of Errol clay. Some discreet clay domains were visible within the mixed matrices, indicating that the material had not been worked through enough to achieve the complete combination of the Errol clay and aggregate material. This is a problem identified by McLaughlin (forthcoming) in relation to repair materials used in Scotland and serves to reflect the difficulties encountered when trying to replicate historic processes in a representative way. When viewed microscopically, however, the similarities in coarse/fine distribution patterns between the mixed composition experimental materials and the field samples do at least indicate that the material was generally well mixed and that some representivity of historical materials was achieved. The issue of fine material loss noted as having occurred during the manufacture of thin sections from field samples also occurred in relation to the experimental thin sections.

10.3.1.3 Results

The contrasts between the sections, depending upon the treatments that the original blocks were subjected to, are limited but highlight distinct points of interest that also have ramifications when related to the evidence provided from the field samples. The primary points of contrast relate to the types of microstructure exhibited and relative development of accommodating planes and vughs, depending upon treatment. It would appear that vughy microstructures are typical for the mixed composition blocks, with these developing into crumb microstructures, whereby vughs are increasingly interconnected, apparently as a consequence of greater environmental pressure. This is suggested by the microstructural differences between the samples subjected to “Winter-spring wet baseline” and those subjected to the “dry” and “2080s” cycles. Differences in the extent to which planes and vughs are exhibited between the same samples are difficult to discern, although the 100% clay blocks are structurally distinct from the mixed composition blocks in all of the experimental sets. These materials are typically fissured, with the originally massive microstructure being separated by accommodating planes. These planes are dominant in the “Winter-spring wet baseline” section and frequent to very frequent in the other 100% clay blocks subjected to “winter-spring” experimental conditions. In the 100% clay blocks subjected to freeze-thaw cycles, these fissured microstructures are further developed, with the complete dissociation of material in the “Freeze-thaw baseline” example manifesting in a highly separated angular blocky microstructure, dominated by accommodating voids. In contrast, the same block type was only weakly separated when exposed to the equivalent 2080s experimental cycle, with structural integrity retained.

The relative absence in the experimental materials of pedofeatures of a type identified in the field sample materials is noteworthy, as this suggests that their fuller development is reliant upon longer-term exposure to the conditions of repeated wetting and drying and freeze-thaw that the experiments attempted to replicate. Likewise, this adds credence to the notion that those pedofeatures observed in the sampled materials developed *in situ* and are therefore likely to be products of dynamic processes within the walls. Infillings of clay within pore spaces were noted in some experimental materials, however, particularly in “Winter-spring wet baseline” and “Winter-spring wet 2080s” sections, which indicates the effects of water translocation of the fine fraction. Furthermore, the “Freeze-thaw 2080s” 100% clay block includes clay infillings and Fe/Mn pedofeatures. These are absent from the equivalent block subjected to “Freeze-thaw baseline” conditions, although it should be remembered that this material was sampled in a state of failure. It is important to note that evidence of salt crystallisation within the materials subjected to the Freeze-Thaw experiments was also absent and the possible impacts of the solution applied at the start of the experimental cycles are thus discounted.

Table 10.7. Summary table of micromorphological observations of thin sections derived from experimental materials.

Treatment	Thin Section by clay content	Structure			Groundmass										Pedofeatures			
					Coarse Mineral Material (>63 µm)				Fine Mineral Material (<63 µm)			Coarse Organic Material (>63 µm)			Clay		Fe/Mn oxide	
		Microstructure	Accommodating planes	Vughs	Quartz/Feldspar	Muscovite/ Biotite/ horn	Granite/ Gneiss/pegmatite	Phytoliths	Nature of fine mineral material (PPL)	Groundmass b Fabric (XPL)	C/f distribution pattern	Straw	Wood fragments	Plant tissue	Infillings	Coatings/hypocoatings/ capping	Matrix impregnation/ coatings/hypocoatings	Nodules
Winter-spring Dry Baseline	15	Vughy	*	**	***	t			Dark brown	Undifferentiated	Close / single spaced porphyric	***	t	t				
	20	Vughy	t	**	***	t			Dark brown	Undifferentiated	Close / single spaced porphyric	***		t				
	25	Vughy	*	**	***	t			Dark brown	Undifferentiated	Close / single spaced porphyric	***						
	100	Fissured; locally massive	*		*				Brown	Stipple-speckled	Open porphyric		t		t			
Winter-spring Wet Baseline	15	Crumb	*	**	***	t			Dark brown	Undifferentiated	Close / single spaced porphyric	***		t	#			
	20	Crumb	*	***	***	t			Dark brown	Undifferentiated	Close / single spaced porphyric	***	t	t	t	t		
	25	Crumb	**	***	***	t			Dark brown	Undifferentiated	Close / single spaced porphyric	***		t	#			t

	100	Fissured; locally massive	****	t	*				Brown	Stipple-speckled	Open porphyric		t	t	#		t	
Winter-spring Dry 2080s	15	Vughy	*	*	***	t			Dark brown	Undifferentiated	Close / single spaced porphyric	***		t				
	20	Vughy	*	**	***	t			Dark brown	Undifferentiated	Close / single spaced porphyric	***	t					
	25	Vughy	*	*	***	t			Dark brown	Undifferentiated	Close / single spaced porphyric	***		t				
	100	Fissured; locally massive	**	*	*				Brown	Stipple-speckled	Open porphyric			t				
Winter-spring Wet 2080s	15	Vughy	*	**	***	t			Dark brown	Undifferentiated	Close / single spaced porphyric	***		t	#			
	20	Vughy	*	**	***	t			Dark brown	Undifferentiated	Close / single spaced porphyric	***		t	t			
	25	Crumb	*	***	***	t			Dark brown	Undifferentiated	Close / single spaced porphyric	***	t	t	t			
	100	Fissured; locally massive	***		*				Brown	Stipple-speckled	Open porphyric		t		##		#	t
Freeze-thaw Baseline	15	Vughy / crumb	***	***	***	t			Dark brown	Undifferentiated	Single spaced porphyric	***		t				
	20	Vughy / crumb	***	***	***	t			Dark brown	Undifferentiated	Single spaced porphyric	***		t				
	25	Vughy / crumb	***	***	***	t			Dark brown	Undifferentiated	Single spaced porphyric	***		t	#			

	100	Highly separated angular blocky; locally massive	****	**	*				Brown	Stipple speckled	Open porphyric					t		
Freeze-thaw 2080s	15	Vughy / crumb	**	***	***	t			Dark brown	Undifferentiated	Single spaced porphyric	***	t	t				
	20	Vughy / crumb	**	***	***	t			Dark brown	Undifferentiated	Single spaced porphyric	***		t				
	25	Vughy / crumb	**	***	***	t			Dark brown	Undifferentiated	Close / single spaced porphyric	***		t	##			
	100	Weakly separated angular blocky; locally massive	*	t	*				Brown	Stipple speckled	Open porphyric				##		t	t
Frequency class refers to the appropriate area of section																		
t = trace (<1%) * = very few (1 - 5%) ** = few (5 - 15%) *** = frequent (15 - 30%) **** = very frequent (30 - 50%) ***** = dominant (>50%)																		
Frequency class for pedofeatures																		
t = trace (<1%) # = rare (1 - 2%) ## = occasional (2 - 5%) ### = many (5 - 10%)																		

10.3.2 Image analysis of experimental material

10.3.2.1 Methods

The image analysis protocols followed those for the field sample thin sections.

10.3.2.2 Results

Following the image analysis procedures previously established, the data generated from the experimental materials was also filtered based on the maximum Feret diameter measurements for each originally identified pore space. This also manifested in a reduction in the size of the dataset without greatly affecting overall porosity values (Figs. 4.10 and 4.11).

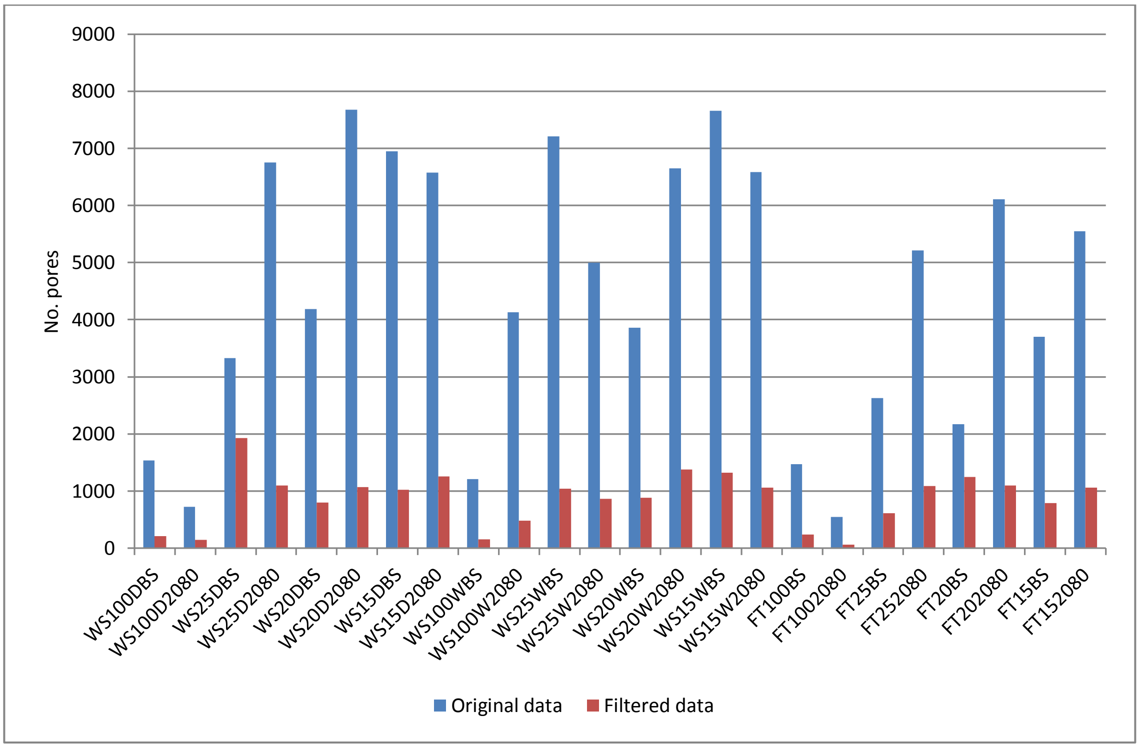


Fig. 10.10. Number of pore spaces identified for each thin section, showing original and filtered data.

Clear divisions between the 100% clay blocks and the mixed composition blocks are seen. Lower porosity values are exhibited by all of the 100% clay blocks within the "Winter-spring" treatment group compared with the mixed composition blocks. It is interesting to note that of these 100% clay blocks, it is that which was subjected to the "wet 2080s" experimental cycle that has a distinctly increased number of pores (Fig. 10.10) and greater overall porosity. It is tempting to speculate whether higher temperatures equated to increased water transport during the "winter" phase of the 2080s cycle when compared with the same point of the baseline cycle. In the latter case water inside the blocks would not necessarily have frozen, despite the freezing conditions (as demonstrated through internal wall temperature data for Cottown Schoolhouse and Flatfield Steading), whilst external water would have frozen and therefore been inhibited from moving into the blocks. This again highlights the importance of recognising increased dynamic water movement impacts under future climate conditions. It is difficult to discern distinct trends in the data across the mixed composition blocks, with results variable in relation to both treatment and clay content. Porosity is greater for each block type treated to "Winter-spring dry baseline" conditions when compared with the equivalent projected conditions, other than the 15% clay examples. Under each of the "Winter-spring wet" climate conditions, 100% and 25% clay content resulted in greater porosity under the future projected scenario, whilst 20% and 15% clay content resulted in greater porosity values under baseline conditions.

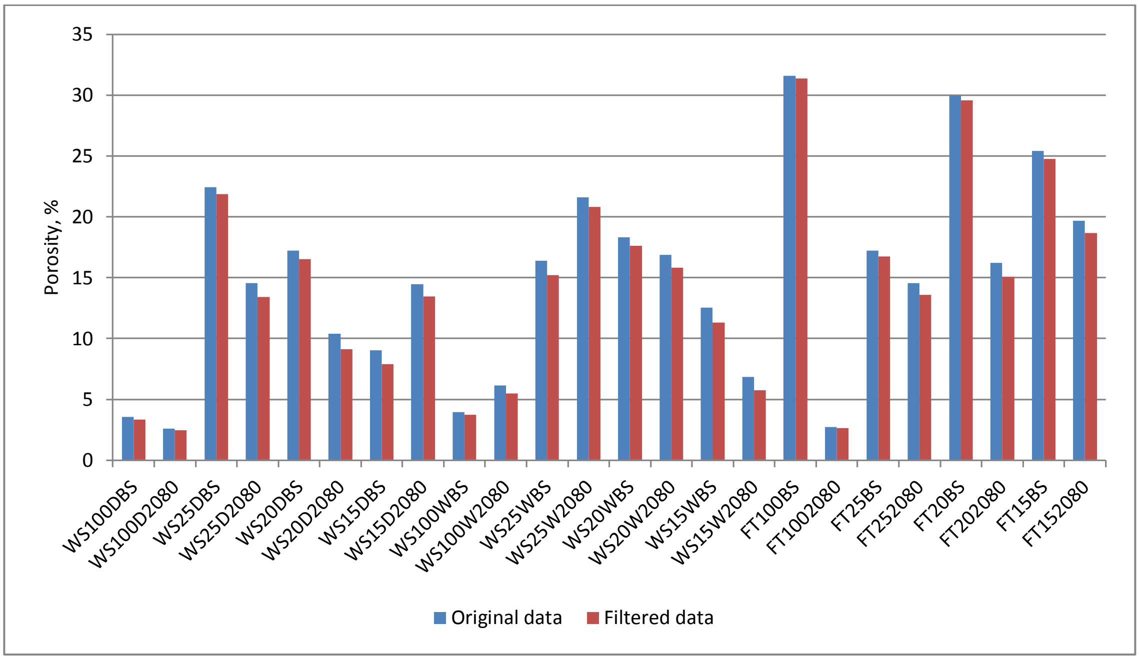


Fig. 10.11. Percentage porosity exhibited across the thin sections, showing original and filtered data.

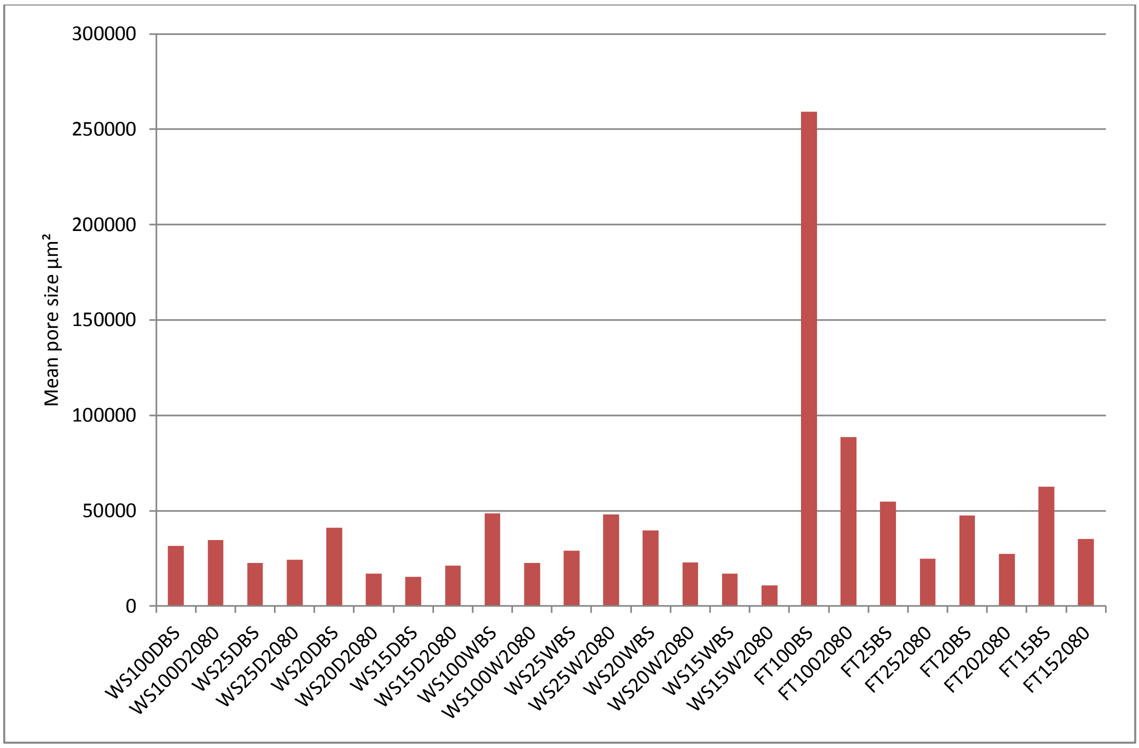


Fig. 10.12. Mean pore size values across the thin sections, based on filtered results.

The results for the 100% clay blocks subjected to the divergent “Freeze-thaw” conditions are starkly contrasted, with the baseline conditions resulting in complete failure. The relative divergence in the number of pores in each of these samples is much smaller than that for overall porosity, which reflects the extent to which the material separated and pores became interconnected. For the “Freeze-thaw” blocks it is interesting to note that those mixed composition blocks subjected to 2080s conditions each contain more pores than the equivalent block subjected to baseline conditions, yet this relationship is inverted in relation to overall porosity. This indicates a greater interconnectedness of pore space, with slightly more developed planar voids being a manifestation of ice separation that is also reflected in slightly increased pore elongation. The porosity of the section derived from the 20% clay block subjected to “Freeze-thaw baseline” conditions is almost as great as that exhibited in the equivalent 100% clay section. Nevertheless, the block from which this section derives did not suffer complete failure and this reflects the importance of aggregate materials in maintaining structural integrity. It is also tempting to speculate as to whether this offers insight as to the critical point at which structural failure may occur through freeze-thaw induced material dissociation. The relatively low porosity value for the section derived from the 25% clay “Freeze-thaw baseline” block also serves to further illustrate the inherent resilience of mass earth materials to environmental pressures, although when the results of the two experiments are viewed together there are no clear conclusions to be made in terms of the relationship between clay content and resilience. Some further evidence of material resilience is however seen in terms of the range of mean Feret diameter measurements (Fig. 10.13) across the experimental sections, with only the sections derived from 100% clay “Freeze-thaw” experiment blocks diverging notably from the ranges exhibited by the remaining blocks over each experimental group.

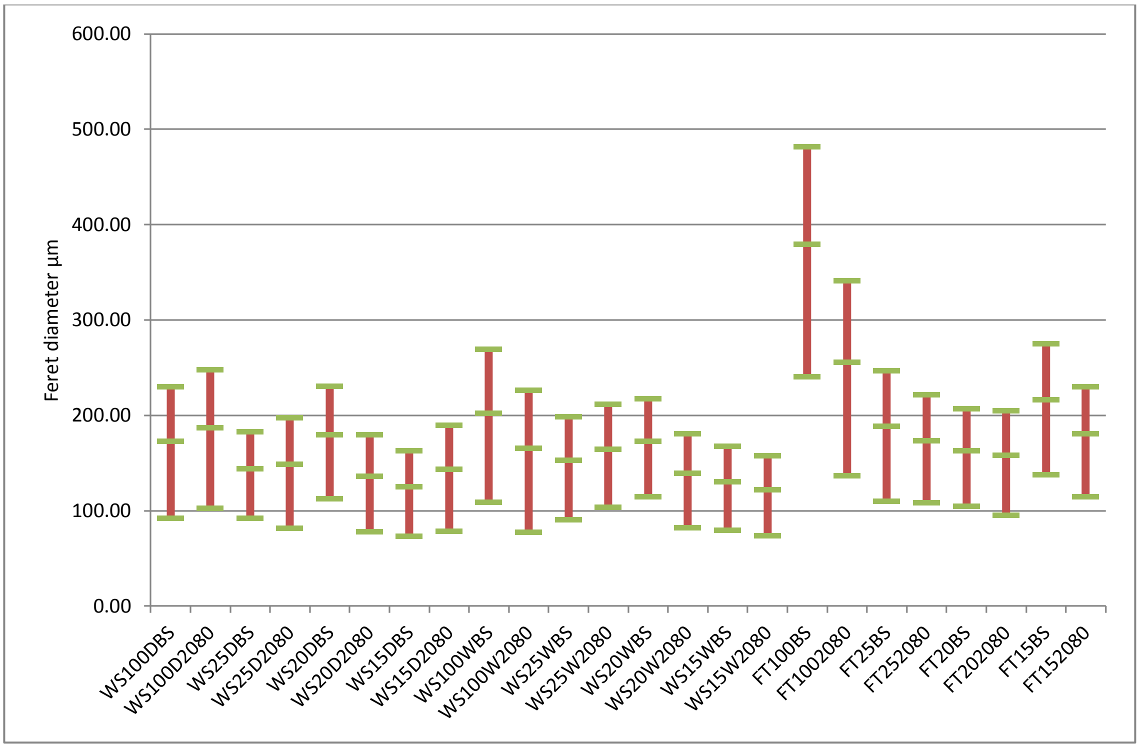


Fig. 10.13. Mean minimum, mean maximum and mean of mean Feret diameter values across the thin sections, based on filtered data.

Table 10.8. Summary table of filtered image analysis data for thin sections derived from experimental blocks.

	Composition						Shape						Connectivity						Porosity		
Thin section	Clay, %	Soil, %	Gravel, %	Straw, %	Treatment	Pores, n	Mean SF	Mean Sph.	Mean El.	SD SF	SD Sph.	SD El.	Mean min Feret dia. µm	Mean max Feret dia. µm	Mean of $\bar{x}$ Feret dia. µm	SD min Feret dia. µm	SD max Feret dia. µm	SD $\bar{x}$ Feret dia. µm	Mean pore size µm²	SD pore size µm²	% porosity
WS100DBS	100	0	0	0	Winter-spring dry baseline	211	0.13	0.21	3.20	0.07	0.18	2.11	92.16	229.25	172.57	148.38	386.83	286.81	31541	208416	3.34
WS100D2080	100	0	0	0	Winter-spring dry 2080s	143	0.28	0.21	3.37	0.13	0.21	2.33	102.17	247.26	186.64	144.75	351.37	257.60	34598	172475	2.48
WS25DBS	25	66	8	1	Winter-spring dry baseline	1931	0.14	0.26	2.65	0.10	0.19	1.73	92.14	182.29	143.53	153.21	317.89	244.77	22569	179147	21.87
WS25D2080	25	66	8	1	Winter-spring dry 2080s	1100	0.18	0.20	3.35	0.10	0.18	2.51	81.13	196.85	148.63	135.09	319.90	240.79	24277	305900	13.40
WS20DBS	20	71	8	1	Winter-spring dry baseline	803	0.18	0.26	2.54	0.10	0.19	1.44	111.89	229.81	179.16	199.22	453.09	336.86	41035	341392	16.54
WS20D2080	20	71	8	1	Winter-spring dry 2080s	1072	0.16	0.21	3.05	0.09	0.18	1.92	77.17	179.01	135.83	116.35	317.29	227.50	16973	131812	9.13
WS15DBS	15	76	8	1	Winter-spring dry baseline	1026	0.17	0.21	3.07	0.10	0.18	1.88	72.89	162.66	124.69	102.01	251.89	185.00	15366	90717	7.91
WS15D2080	15	76	8	1	Winter-spring dry 2080s	1256	0.16	0.19	3.57	0.09	0.18	2.69	78.20	189.13	142.72	140.58	311.29	233.53	21321	213821	13.44
WS100WBS	100	0	0	0	Winter-spring wet baseline	154	0.20	0.22	3.13	0.12	0.19	2.31	108.57	268.89	201.46	177.06	577.97	405.26	48757	227782	3.74
WS100W2080	100	0	0	0	Winter-spring wet 2080s	482	0.23	0.18	4.17	0.13	0.19	3.39	76.91	226.00	165.29	121.42	421.98	296.13	22623	150930	5.47
WS25WBS	25	66	8	1	Winter-spring wet baseline	1044	0.16	0.21	3.15	0.09	0.18	2.08	90.06	198.13	152.11	199.32	395.22	308.02	29064	254187	15.23

WS25W2080	25	66	8	1	Winter-spring wet 2080s	865	0.17	0.24	2.73	0.10	0.19	1.56	103.19	211.12	164.05	227.21	459.37	355.25	47938	479911	20.81
WS20WBS	20	71	8	1	Winter-spring wet baseline	887	0.26	0.25	2.59	0.14	0.19	1.42	114.11	217.42	172.44	213.13	333.91	273.36	39586	284924	17.62
WS20W2080	20	71	8	1	Winter-spring wet 2080s	1378	0.18	0.21	3.22	0.10	0.19	2.32	81.68	180.36	138.72	152.79	286.29	224.27	22887	246206	15.82
WS15WBS	15	76	8	1	Winter-spring wet baseline	1318	0.19	0.23	2.95	0.12	0.19	1.90	79.36	167.23	129.71	127.32	271.13	204.94	17068	128500	11.29
WS15W2080	15	76	8	1	Winter-spring wet 2080s	1056	0.18	0.23	2.90	0.10	0.19	1.79	73.43	157.28	121.64	88.73	232.82	169.06	10852	60177	5.75
FT100BS	100	0	0	0	Freeze-thaw baseline	241	0.20	0.23	3.10	0.11	0.19	2.08	240.33	480.98	378.95	589.96	1012.43	829.00	259231	1226072	31.36
FT1002080	100	0	0	0	Freeze-thaw 2080s	59	0.21	0.22	2.85	0.13	0.20	1.40	135.86	340.54	255.46	231.96	634.93	469.18	88612	403841	2.62
FT25BS	25	66	8	1	Freeze-thaw baseline	609	0.25	0.21	3.16	0.14	0.19	2.01	109.22	246.29	187.93	243.44	493.16	382.86	54837	445532	16.76
FT252080	25	66	8	1	Freeze-thaw 2080s	1088	0.23	0.25	2.58	0.13	0.19	1.35	107.90	221.09	172.97	132.47	294.31	225.52	24905	113054	13.60
FT20BS	20	71	8	1	Freeze-thaw baseline	1243	0.13	0.24	2.87	0.08	0.19	1.88	104.26	206.61	162.54	255.79	424.15	344.64	47409	499169	29.58
FT202080	20	71	8	1	Freeze-thaw 2080s	1094	0.24	0.23	2.84	0.14	0.19	1.80	94.58	204.51	157.93	162.96	363.07	277.83	27438	232106	15.07
FT15BS	15	76	8	1	Freeze-thaw baseline	787	0.24	0.25	2.74	0.15	0.20	1.73	137.05	274.93	216.04	268.20	496.95	395.32	62695	447413	24.76
FT152080	15	76	8	1	Freeze-thaw 2080s	1060	0.22	0.25	2.58	0.11	0.19	1.30	114.56	229.62	180.45	188.62	396.90	302.90	35111	234811	18.68

*SF refers to shape factor; Sph. refers to sphericity; El. Refers to elongation

10.3.2.3 Statistical analyses

Following the same procedures outlined as for the statistical analyses of the field sample materials, and also accounting for the same limitations, statistical analyses of the experimental materials were conducted in order to determine whether apparent differences between the datasets could be attributed to divergences in material composition and the experimental treatments to which the original blocks were subjected. The results are presented in tables of interaction between thin sections derived from all of the experimental blocks in each group and the results of tests based on comparisons between block types and treatments for each experimental group are presented in Table 10.9, below. As for the thin sections derived from field sample materials, no significant differences in subsample variation were observed for either experimental group, thus validating comparisons between sections.

Some of the most striking results of the interaction observations made between each of the blocks subjected to “Winter-spring” experimental treatments include the greater number of significant results returned for interactions involving each of the sections derived from 100% clay blocks subjected to future conditions when compared with the equivalents subjected to baseline conditions. It is also interesting to note that the only significant difference observed between the 100% clay sections subjected to each of the “Freeze-thaw” treatments was for maximum Feret diameter. It is again difficult, however, to discern distinct trends based on the interactions between each of the mixed composition blocks and this perhaps makes the summary results (Table 10.8) more informative to this discussion.

Significant differences in shape factor were found in all interactions based on clay content and treatment, except for that between the 25 and 15% clay blocks in the “Freeze-thaw” experimental group. All interactions based on clay content indicated significant differences within the “Winter-spring” experimental group, with the exception of the pore size areas exhibited in the 100% and 20% clay sections. All differences in shape values were significant in the interactions between the four “Winter-spring” experimental treatments. Significant pore measurement values were only seen for minimum Feret diameter values in relation to six of the eight treatment interactions and in the case of the pore size area measurements between the “Winter-spring wet baseline” and “wet 2080s” treatment groups. The “Freeze-thaw” experimental treatments returned significant differences between each set of results, which were obtained without recourse to Bonferroni *post hoc* analysis.

Table 10.9. Table of interactions for experimentally-derived thin sections, indicating whether differences in features between samples and between treatments are significant (α=0.05).

			SF	Sph	El	F Min	F Max	F Mean	Area
Winter-Spring	Block type interactions	100-25	/	/	/	/	/	/	/
Winter-Spring	Block type interactions	100-20	/	/	/	/	/	/	X
Winter-Spring	Block type interactions	100-15	/	/	/	/	/	/	/
Winter-Spring	Block type interactions	25-20	/	X	X	X	X	X	X
Winter-Spring	Block type interactions	25-15	/	/	/	/	/	/	/
Winter-Spring	Block type interactions	20-15	/	/	/	/	/	/	/
Winter-Spring	Subsample interactions*		X	X	X	X	X	X	X
Winter-Spring	Treatment interactions	WSD2080-WSDBS	/	/	/	/	X	X	X
Winter-Spring	Treatment interactions	WSD2080-WSW2080	/	/	/	X	X	X	X
Winter-Spring	Treatment interactions	WSD2080-WSWBS	/	/	/	/	X	X	X
Winter-Spring	Treatment interactions	WSDBS-WSW2080	/	/	/	/	X	X	X
Winter-Spring	Treatment interactions	WSDBS-WSWBS	/	/	/	X	X	X	/
Winter-Spring	Treatment interactions	WSW2080-WSWBS	/	/	/	X	X	X	X
Freeze-Thaw	Block type interactions	100-25	/	X	X	X	X	X	X
Freeze-Thaw	Block type interactions	100-20	/	/	/	X	/	X	/
Freeze-Thaw	Block type interactions	100-15	/	X	X	X	X	X	X
Freeze-Thaw	Block type interactions	25-20	/	/	/	/	/	X	/
Freeze-Thaw	Block type interactions	25-15	X	X	X	X	X	X	X
Freeze-Thaw	Block type interactions	20-15	/	/	/	/	/	X	/
Freeze-Thaw	Subsample interactions*		X	X	X	X	X	X	X
Freeze-Thaw	Treatment interactions		/	/	/	/	/	/	/

*Determined by whether >50% of all subsample interactions deliver significant results
“/” = statistically significant (α=0.05); “X” = not statistically significant.

It is worth noting that each group of thin sections, including those derived from field samples as well as from experimental materials, was determined to be significantly different from the other for all of the observations (Table 10.10). This encapsulates the extent to which the micro-structural characteristics of these mass earth materials diverge as a consequence of original provenance and the effects of external conditions.

Table 10.11. Table of interactions comparing the field sample group results, “Winter-spring” group results and “Freeze-thaw” group results.

	SF	Sph	El	F Min	F Max	F Mean	Area

Field-Freeze-Thaw	/	/	/	/	/	/	/
Field-Winter Spring	/	/	/	/	/	/	/
Freeze-Thaw-Winter Spring	/	/	/	/	/	/	/
"/" = statistically significant (α=0.05); "X" = not statistically significant.							

10.4 Conclusion

A number of benefits and limitations to the use of micromorphological and micromorphometric analysis techniques, including the procedures used to obtain the thin sections analysed, have been outlined here. Geoarchaeological approaches have been hitherto underused in the main tranche of mass earth building studies, but can be highly informative and offer the opportunity to relate micro-scale processes with macro-scale environmental context and deterioration. This is borne out in the evidence of redoximorphic and clay translocation pedofeatures, together with porosity measurements reflective of structural change, within the thin sections derived from field samples. The heterogeneity of mass earth building materials, even when formed of the same basic constituents, is also reflected micromorphologically with structure influenced by original construction techniques and the environmental pressures experienced post-erection. This point also holds true for the experimental materials and ultimately highlights the importance of intra-site appraisals during conservation studies.

The limitations of the image analysis procedures were recognised and subsequently handled in a logical way that was validated through the limited impact of data filtration on overall porosity results. It was interesting to note that although the Cottown Lower section was clearly the most deteriorated of those derived from field samples, it still exhibited a lower porosity value than for several of the experimental sections. Of these, structural failure was only seen in the 100% clay "Freeze-thaw baseline" section, which was in turn the only section with a porosity value of over 30%. Perhaps the most revealing outcomes from the controlled environment study were those for blocks composed purely of Errol clay, which offer the most well-focused insights into the most critical soil fractions in terms of the cohesion of earth building materials. Minimum Feret diameter measurements seem more sensitive to variations between sections and can therefore be considered a better indicator of structural complexities, with this aspect of pore space perhaps crucial to the development of the more consistently-sized maximum Feret diameter measurements. This is not borne out in the mean data but becomes apparent through consideration of the statistical evidence. Image analyses also revealed interesting results in terms of the representation of pore spaces through shape values. Shape factor is clearly highly sensitive to variation between samples, whereas sphericity and elongation perhaps offer more comparable insights that reflect structural characteristics more generally. Furthermore, the calculation from which these values are made are linked and this offers another benefit when they are used in tandem.

XRCT offers a further layer of insight into a range of structural characteristics, with the great benefit of providing connected data in three dimensions. Clearly the application of XRCT needs to be refined and developed in a more integrated way than could be achieved here. The study has, however, proved to emphasise the importance understanding materials with mixed matrices in three dimensions and offered the opportunity to explore the utility of XRCT as an adjunct to the primary thin section analyses, providing vital experience that can be exploited in future investigations.

Conclusions

11. The past ubiquity, present invisibility and future vulnerability of Scotland's earth-built heritage

This thesis has sought to provide novel insights into the nature, extent and scientific assessment of Scotland's earth-built heritage, with a view to encouraging reappraisals of methodological approaches to an undervalued yet fundamental aspect of the nation's cultural heritage portfolio. The value of the vernacular as a means of embodying a range of tangible remnants and intangible aspects of traditional life, as well as offering food for thought in contemporary approaches to construction and energy consumption, has remained on the fringes of interest and been the reserve of too few scholars and practitioners for too long. In turn, too few of the available means of scientific assessment that are increasingly accessible to researchers of built heritage have been employed in this context. Vernacular earth buildings deserve greater recognition within the fields of historic and scientific conservation enquiry, offering opportunities for interdisciplinary research and collaboration. The attempt to present and promote a logically-structured interdisciplinary approach to earth buildings' research using hierarchies of scale, both in philosophical and practical senses, has therefore been integral to this thesis. It is hoped that this approach will contribute to extending the boundaries of research conducted in relation to earth-built heritage conservation, with the systematic implementations of restoration and repair and procedures given priority over the many *ad hoc* approaches typically relied upon.

11.1 Past ubiquity and present invisibility

'Whatever loses its meaning with social and cultural change, and whatever is forgotten with the passage of time and the changing of context, disappears from general or daily use; a building, an object, even an entire city is finally lost and ends up in the earth' (Vaccaro, 1996, 203).

Earth building traditions have been fundamental to human societies across vast swathes of the world for millennia and in many locations they remain still living. This serves to emphasise, through stark contrast, the discontinuity of Scotland's own traditions in earth building and, conversely, the wide cultural significance embodied within surviving examples. Interest in Scotland's earth-built heritage has, however, remained sporadic and knowledge of it limited. This has served to contribute to the physical and metaphorical invisibility from which it suffers (Fig. 11.1), with this manifesting in turn in a lack of statutory protection for many more buildings than those presently recognised. It is contended here that an absence of historical approaches to the subject using documentary sources and an over-reliance on field survey has contributed to the endurance of skewed perspectives of Scotland's earth building traditions, as well as an under-appreciation of the diverse social contexts in which earthen materials were employed. A substantial amount of work remains to be conducted in this area, using documentary evidence as a means of fully exploring the myriad past practices of Scottish earth building above and before contemporary re-interpretations of building methods.

Fig. 11.1. The mudwall farmhouse on MOD land at West Freugh serves as a prime example of the issue of invisibility, with its form and superficial appearance belying the original means of construction and materials and methods employed. Its demolition has meant the loss of a sound mass earth structure that also included marked Baltic timbers and sarked roof construction, which was made possible through the further industrialisation of timber production from c. 1800 (Historic Scotland, 2006). (Image courtesy of Stranraer Museum).

The historian is of primary importance to understanding and thus informing the management and conservation of the cultural and built heritage and this is an important consideration with regards to Scotland's earth building traditions and the often isolated and hidden vestiges that continue to embody them. Those historic mass earth buildings that have been recognised in Scottish landscapes since the latter-half of the twentieth century are generally eighteenth and nineteenth century structures and the medieval origins of mudwall building are of importance to this thesis as a means of recognising the depth of cultural traditions demonstrated in the more recent examples now of heritage interest. Just as mass earth traditions encompass more locations than the Carse of Gowrie, however, the earth building traditions of Scotland clearly encompass so much more than mass earth and it is important to recognise the individual characteristics of the myriad materials and methods of construction that are conveniently captured under the umbrella of "earth building". This ultimately validates the close foci on mudwall and local considerations taken in this thesis, simultaneously highlighting the need to commit future work to a range of other earth building contexts.

11.1.1 Future historical research

The limited base from which to draw established information relating to Scotland's earth building traditions means that inferences have been sought from a wide variety of sources, ultimately helping to inform interpretations locally, but this does not in itself mean that there is not further evidence to be discovered in archives across Scotland. The historical research conducted for this thesis was inevitably constrained by the interdisciplinary nature of the research project as a whole, but this means there are myriad opportunities to build upon and develop the inferences gained up to this point. The further investigation of less well-known enclaves of mass earth should be considered a priority, as too should those relating to the past applications of mud mortar and turf. The materials and methods embodied therein are highly contrasted in terms of their use and contemporary proliferation but all are vitally important to the heritage narrative and as opportunities for exploring aspects of social status and cultural continuities pertinent to Scottish, North Atlantic and mainland European history. It is clear that dedicated historical research could and should form the basis of future research projects, allowing for wide geographical coverage and providing deeper temporal insights than hitherto achieved. The outcomes of such a process can then be further integrated with established and novel approaches to assessing buildings' performance, as achieved in this thesis, in order to promote holistic conclusions with wider impacts.

11.2 Future vulnerability

Scotland's climate has observably changed over recent history and will continue to change at an accelerated rate with the perpetuation of current socio-economic and political conditions. This thesis therefore rests within the crux of the most prominent contemporary concern regarding the historic environment. Climate change impacts are highly complex and variable in terms of the ways they may manifest in relation to the built heritage and thus present many challenges in relation to the management of heritage assets. Concerns over the impacts of freeze-thaw stressing in the present should become secondary to considerations of dynamic water movement. The increased potential for salt damage to occur in the future requires further research. The importance of localised approaches has been repeatedly emphasised throughout this thesis and it is vital that future climate implications are considered at the kind of scales considered here, with projections made at 5 km^2 spatial resolution being easily replicated across other areas of interest. This also corresponds with locally-focused approaches advocated in the most recent Scottish Historic Environment Policy documents (Historic Scotland, 2009, 2011).

Common phrasing such as "climate change impacts" may encourage assumptions as to purely negative implications. It is important to note, however, that climate changes could alleviate the impacts of certain deteriorative phenomena such as freeze-thaw cycles. Indeed, a reduction in the frequency of freeze-thaw cycles can be expected over the course of the twenty-first century, thus reducing the threats that these pose to buildings such as the Old Schoolhouse, Cottown. This change, superficially of benefit in ensuring the integrity of the building fabric, is not as straightforward as may be presumed. It has been shown in this thesis that the impacts of dynamic water movement are intrinsic to processes of shrink-swell, clay translocation and structural change at the micro-scale, all of which can be monitored at the macro-scale using apparatus such as microwave moisture sensor apparatus. Taking the examples of Cottown Schoolhouse and the barn at Flatfield Steading, it is clear that an inherent resilience not always appreciated is embodied within these structures and this is explained at least in part by the results of wall internal temperature monitoring that highlights a resistance to low external temperatures experienced during a Scottish winter. This, together with the knowledge that higher mean winter temperatures and increased incidences of winter precipitation are increasingly likely for the remainder of the twenty-first century, indicates that the threats posed by freeze-thaw may well have been relatively limited in the past and will be far outweighed by the impacts of increased dynamic water movement in future winters. This must therefore be deemed a crucial consideration when formulating management strategies into the future.

11.2.1 Comments on the technical approaches reported in this thesis

The definitiveness of the conclusions stemming from this thesis are arguably limited by the relatively small number of sample sites and the use of larger-scale actualistic experiments, which were consciously chosen in favour of smaller-scale experiments in order to obtain more representative insights. The limit placed on sampling is also an integral strength of the research, however, as the concentration of investigations at the Old Schoolhouse, Cottown, has allowed for a comprehensive set of techniques to be applied and judgements made as to the relative applicability of the novel approaches employed. Soils are highly variable, even within small geographic areas where certain geological conditions predominate, and this further emphasises the importance of localised, intra-site approaches to research in this area. Technical definitions of soils used in earth building could be formalised across the field of interest, based on the understandings of soil science rather than practitioner-led interpretations that often stem from engineering and architectural conservation perspectives. The concentration of resources within a small area has also allowed for this thesis to demonstrate the efficiency with which sampling procedures involving portable, non-intrusive equipment can be implemented and replicated, therefore presenting an opportunity to quickly build an integrated and more comprehensive evidence base with relevance to contemporary agenda.

11.2.2 Future technical research

The sampling procedures upon which the latter part of this thesis has been based were originally foreseen as centring upon micromorphological and micromorphometric analyses. Consequently, extracted material samples were taken, impregnated and processed in the first part of the project. Over the course of the research, however, it was determined that the scope of the sampling initiatives originally devised could be extended considerably based upon the macro-scale investigations outlined. Furthermore, the opportunity to explore the utility of XRCT in this novel context emerged relatively late in the research period and, though informative, could yield more beneficial results when repeated as part of a refined series of sampling methodologies. It is therefore important that the lessons learnt through the research from which this thesis emanates should be used as the basis for suggesting a refined, integrated sampling model that can be repeated, using the same apparatus, in the future.

11.2.2.1 A refined model for sampling the earth-built heritage

In order that future work may be conducted with the greatest possible efficiency based on the procedures discussed in this thesis, an idealised model of intra-site sampling is proposed using the following steps:

- Target specific points of interest within a given structure, such as those known to suffer from particular environmentally-driven issues of deterioration or areas known to have been repaired and where interfaces between original and introduced material can be identified.
- Use cylindrical cores to remove material from the mass earth wall at various heights and locations within the structure, ensuring that this is done in a way that retains the structural integrity of the extracted material and that a horizontal transect of material from the internal surface to deep within the wall is obtained. The extremely solid nature of dry mudwall material means that a robust core must be used to carry this out.
- Simultaneously, establish a series of MMS sampling across the given structure, with a view to this being conducted at regular intervals throughout the research period. If possible, use sensor heads that will give results for the material near the wall surfaces as well as at depth.
- Instrument the building with temperature and humidity data loggers, plugging the holes from where material was extracted with suitable local clay soil mixed with chopped straw to avoid shrinkage. Periodically acquire the recorded data. Preferably, develop a means of achieving this remotely without the necessity of making a physical connection with the data logger.
- Impregnate the extracted material with (preferably dyed) resin and scan each sample using XRCT. Once this has been done make thin sections from intervals of material

running from the wall surface to the wall interior. These can be assessed using micromorphology and image analysis, with extension of the procedures used in this thesis to include such analyses as scanning electron microscopy (SEM) or gain further insights using XRF.

- Use leftover material, ensuring that it has not been exposed to light, to conduct optically stimulated luminescence dating. Considerations of the utility of this technique were made early in the research project and commented upon in the conference proceedings for *Terra 2012* (Adderley *et al*., 2012). Optically stimulated luminescence dating offers an opportunity to gain insights into the relative date of materials used in construction and may reveal disparities between the lifts within the wall if constructed over a number of building seasons or, more usefully, indicate areas where repairs may have been carried out over time.

This guide to replicating the sampling methods discussed in this thesis offers the potential for future refinement through repeated application. The utility of the technologies employed is yet to be fully explored and it is vital that the value to be gained from using multiple approaches simultaneously is recognised as a means of extending the evidence base from which management decisions are formed.

11.3 Final remarks

Historic buildings are immovable artefacts and therefore cannot be subjected to laboratory-based analyses without the removal of materials, which is permitted in order to make evidence-based conservation decisions (Burra Charter, 2013) but compromises the principle of minimum intervention that underpins historic built environment policy in the United Kingdom. The principal of minimum intervention clearly limits the amount of material that could ever be extracted from a historic structure, however, thus leaving analyses open to criticisms relating to the limited representivity that a discreet quantity of samples may offer.

This thesis acknowledges the value to obtaining some material for laboratory-based analyses, but also recognises the necessity of allying these to new methods of investigation.

This context, together with the great variability exhibited by earth buildings within even short distances in areas such as the Carse of Gowrie, emphasises the importance of embracing non-intrusive, repeatable portable scientific approaches to accumulating data that can offer useful additional evidence from which historic environment policy and intra-site management decisions may be informed. Understandings of, and approaches to, Scotland's earth-built heritage need to be extended through an increased awareness of, and engagement with, methods of monitoring and analysis that are recognised much more readily amongst those concerned with the conservation of other building materials and heritage artefacts. This should be perceived as an opportunity to provide important new insights as an adjunct to the approaches hitherto relied upon, rather than a threat to the established methods of investigation.

The research from which this thesis is comprised is therefore of profound value to the future conservation of Scotland's earth-built heritage and carries relevance to the built heritage more generally. It can still only be considered a first step in moving the study of Scotland's earth-built heritage forward, however, offering fresh insights and methods that have been so far overlooked. The challenges posed by the research agenda from which this thesis was conceived have been met with varying success and there are undoubtedly a range of key outcomes and insights that provide the basis for future work and help to widen the scope of interest in a way that can engender improved understandings across disciplinary boundaries before being fed back into heritage protection strategies.

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Appendices

Appendix 1: Summary climate data expressed as daily means using outputs from the UKCP09 Weather Generator focused at 5 km resolution on Errol, Carse of Gowrie, Perthshire

Appendix 1.1 Mean daily baseline climate conditions

Month	Day	Total daily precipitation, mm	Minimum daily temperature, °C	Maximum daily temperature, °C	Vapour pressure (hPa)	Relative humidity, %	Sunshine hours, hr	Downward diffuse irradiation (W/m^2)	Direct irradiation (W/m^2)	Daily mean potential evapotranspiration, mm/day
Jan	1	2.18	-1.90	4.27	6.19	0.91	1.19	0.27	0.08	0.28
Jan	2	2.23	-1.59	4.70	6.26	0.91	1.33	0.27	0.09	0.26
Jan	3	2.32	-1.22	4.86	6.47	0.91	1.22	0.29	0.08	0.25
Jan	4	2.24	-1.70	4.21	6.09	0.90	1.60	0.29	0.12	0.25
Jan	5	2.23	-1.26	4.66	6.21	0.89	1.64	0.30	0.12	0.27
Jan	6	2.36	-0.82	5.52	6.62	0.90	1.00	0.30	0.07	0.31
Jan	7	2.31	-0.83	5.50	6.69	0.91	1.20	0.30	0.08	0.29
Jan	8	2.42	-1.93	5.54	6.24	0.88	1.13	0.29	0.08	0.40
Jan	9	2.26	-1.32	4.60	6.35	0.91	0.91	0.30	0.06	0.26
Jan	10	2.36	-0.84	5.90	6.56	0.88	1.51	0.31	0.11	0.43
Jan	11	2.37	-0.96	5.54	6.53	0.90	0.94	0.30	0.07	0.47
Jan	12	2.29	-0.17	6.24	6.77	0.88	1.06	0.31	0.08	0.49
Jan	13	2.37	0.34	5.87	6.57	0.85	1.19	0.31	0.10	0.59
Jan	14	2.35	0.35	6.30	6.91	0.88	1.16	0.34	0.09	0.47
Jan	15	2.37	0.14	5.52	6.71	0.88	1.06	0.34	0.08	0.44
Jan	16	2.36	0.20	5.51	6.51	0.86	1.27	0.34	0.11	0.42
Jan	17	2.43	0.08	5.98	6.69	0.87	1.01	0.34	0.08	0.44
Jan	18	2.31	-0.30	5.95	6.76	0.90	1.24	0.37	0.10	0.37
Jan	19	2.23	0.02	5.35	6.68	0.89	1.65	0.36	0.14	0.35
Jan	20	2.33	0.53	6.09	6.67	0.85	1.13	0.37	0.10	0.51
Jan	21	2.37	-0.01	5.92	6.54	0.85	1.65	0.39	0.14	0.57
Jan	22	2.31	0.51	6.48	6.88	0.86	1.57	0.40	0.15	0.49
Jan	23	2.36	1.31	7.33	7.07	0.83	1.61	0.39	0.16	0.54
Jan	24	2.42	1.23	7.02	7.33	0.88	1.21	0.43	0.11	0.49
Jan	25	2.49	1.13	6.50	7.11	0.88	1.61	0.42	0.16	0.46
Jan	26	2.40	-0.19	5.70	6.75	0.90	0.99	0.43	0.09	0.44
Jan	27	2.38	0.33	5.71	6.65	0.87	1.17	0.42	0.11	0.48
Jan	28	2.47	0.24	6.11	6.68	0.86	1.62	0.49	0.15	0.54

Jan	29	2.37	-0.19	5.89	6.90	0.90	1.70	0.46	0.18	0.41
Jan	30	2.32	0.03	5.64	6.55	0.86	1.48	0.48	0.16	0.51
Jan	31	2.38	0.94	6.26	7.02	0.88	2.06	0.49	0.22	0.46
Feb	32	1.88	-0.20	5.74	6.28	0.83	1.90	0.51	0.21	0.59
Feb	33	1.56	-0.82	5.08	6.31	0.87	1.92	0.52	0.21	0.46
Feb	34	1.73	-1.31	4.60	6.09	0.87	2.13	0.53	0.25	0.44
Feb	35	1.72	-1.68	4.44	5.69	0.82	2.11	0.54	0.24	0.51
Feb	36	1.83	-0.54	5.01	6.23	0.86	2.09	0.54	0.26	0.40
Feb	37	1.87	-0.08	5.21	6.57	0.89	1.94	0.55	0.24	0.42
Feb	38	1.89	-0.29	5.70	6.60	0.88	1.86	0.58	0.22	0.46
Feb	39	1.74	-0.56	5.15	6.20	0.84	2.11	0.58	0.27	0.57
Feb	40	1.76	-0.54	5.07	6.25	0.85	1.55	0.60	0.18	0.51
Feb	41	1.76	-0.62	5.03	6.39	0.88	1.74	0.62	0.22	0.48
Feb	42	1.80	-0.34	5.09	6.12	0.83	1.63	0.61	0.21	0.57
Feb	43	1.87	0.02	5.64	6.46	0.85	1.80	0.64	0.23	0.59
Feb	44	1.80	-0.42	5.45	6.48	0.88	1.94	0.67	0.25	0.55
Feb	45	1.82	0.07	5.48	6.44	0.86	2.18	0.71	0.28	0.55
Feb	46	1.85	-0.22	5.83	6.46	0.85	1.95	0.71	0.25	0.59
Feb	47	1.79	0.35	5.45	6.59	0.87	2.76	0.75	0.37	0.50
Feb	48	1.80	0.00	5.68	6.54	0.86	2.49	0.76	0.35	0.60
Feb	49	1.83	0.26	5.87	6.45	0.84	1.97	0.73	0.28	0.69
Feb	50	1.81	0.33	6.14	6.70	0.86	1.74	0.79	0.24	0.65
Feb	51	1.79	1.04	6.77	6.85	0.83	2.33	0.83	0.31	0.68
Feb	52	1.81	0.66	7.17	6.87	0.84	1.82	0.81	0.26	0.74
Feb	53	1.81	0.25	6.69	6.66	0.84	3.15	0.86	0.48	0.73
Feb	54	1.79	0.12	7.24	7.21	0.89	1.84	0.84	0.27	0.61
Feb	55	1.84	-0.11	6.64	6.80	0.87	2.56	0.87	0.40	0.65
Feb	56	1.90	-1.18	5.91	6.36	0.87	2.53	0.87	0.40	0.64
Feb	57	1.83	-1.28	5.52	6.33	0.88	3.05	0.96	0.47	0.58
Feb	58	1.82	-1.01	5.59	6.33	0.87	2.28	0.93	0.34	0.60
Feb	59	1.83	-1.15	5.35	6.21	0.87	2.44	0.94	0.39	0.65
Feb	60	1.71	0.07	6.85	6.70	0.85	3.17	0.98	0.52	0.72
Mar	61	1.54	0.67	8.24	6.90	0.81	1.82	0.95	0.30	0.92
Mar	62	1.57	0.95	7.67	7.10	0.85	2.45	0.97	0.41	0.83
Mar	63	1.59	0.02	7.43	7.06	0.87	2.15	0.99	0.37	0.74
Mar	64	1.67	0.97	7.84	7.19	0.85	3.32	1.02	0.60	0.70
Mar	65	1.72	1.36	7.88	7.32	0.85	2.76	1.06	0.48	0.84
Mar	66	1.64	0.91	8.18	6.99	0.82	2.11	1.03	0.38	0.97
Mar	67	1.85	0.97	7.69	6.72	0.79	2.64	1.13	0.45	1.01
Mar	68	1.85	1.27	7.90	6.86	0.80	2.77	1.13	0.50	1.06
Mar	69	1.86	1.22	7.71	6.95	0.82	2.94	1.12	0.54	0.95
Mar	70	1.83	1.68	8.34	7.47	0.85	2.11	1.17	0.37	0.86
Mar	71	1.80	1.61	8.91	7.39	0.82	2.18	1.18	0.39	0.96
Mar	72	1.74	0.75	8.92	7.17	0.82	3.96	1.24	0.76	1.06
Mar	73	1.86	0.80	8.29	7.27	0.85	3.02	1.19	0.61	0.92
Mar	74	1.88	0.26	7.41	6.97	0.86	3.01	1.23	0.60	0.92

Mar	75	1.90	0.54	7.76	6.51	0.79	2.39	1.32	0.42	1.14
Mar	76	1.78	1.03	8.09	6.85	0.80	3.28	1.27	0.68	1.11
Mar	77	1.81	1.02	8.51	6.69	0.78	4.06	1.37	0.81	1.29
Mar	78	1.79	1.14	8.30	6.90	0.79	3.17	1.38	0.63	1.20
Mar	79	1.72	0.90	8.42	6.81	0.79	3.51	1.35	0.73	1.27
Mar	80	1.83	1.23	8.51	6.82	0.79	3.09	1.42	0.62	1.30
Mar	81	1.69	1.10	7.97	6.66	0.78	2.80	1.39	0.58	1.24
Mar	82	1.73	1.03	8.20	6.74	0.78	2.73	1.46	0.54	1.21
Mar	83	1.78	0.96	8.30	6.91	0.80	4.20	1.45	0.94	1.26
Mar	84	1.78	1.31	8.23	6.98	0.81	3.89	1.46	0.85	1.26
Mar	85	1.85	0.74	8.08	6.70	0.79	2.81	1.53	0.59	1.33
Mar	86	1.87	1.11	8.47	7.09	0.82	3.32	1.49	0.76	1.22
Mar	87	1.74	1.19	8.50	6.81	0.78	3.47	1.57	0.75	1.33
Mar	88	1.67	1.22	8.58	6.93	0.79	4.10	1.54	0.96	1.31
Mar	89	1.79	1.37	8.20	7.01	0.81	3.15	1.61	0.68	1.30
Mar	90	1.85	1.57	8.84	7.38	0.83	3.53	1.54	0.84	1.27
Mar	91	1.80	1.85	10.50	7.59	0.79	4.37	1.58	1.21	1.41
Apr	92	1.73	2.68	10.07	7.75	0.80	3.97	1.67	1.06	1.45
Apr	93	1.70	2.74	10.00	7.49	0.78	4.51	1.64	1.30	1.60
Apr	94	1.61	1.32	10.29	7.43	0.80	5.29	1.59	1.60	1.55
Apr	95	1.59	2.50	9.86	7.58	0.80	3.93	1.65	1.15	1.49
Apr	96	1.54	2.23	10.01	7.63	0.80	4.48	1.70	1.33	1.49
Apr	97	1.50	1.89	10.37	7.88	0.82	4.22	1.86	1.15	1.46
Apr	98	1.59	2.38	9.86	7.67	0.81	3.61	1.84	0.99	1.49
Apr	99	1.50	2.86	10.44	7.72	0.78	3.25	1.77	0.94	1.58
Apr	100	1.51	2.61	10.66	7.76	0.79	4.28	1.82	1.26	1.63
Apr	101	1.41	2.05	10.51	7.74	0.81	4.01	1.93	1.09	1.61
Apr	102	1.47	1.31	10.01	7.68	0.83	3.99	1.87	1.18	1.48
Apr	103	1.44	1.30	9.72	7.41	0.81	5.45	1.87	1.69	1.56
Apr	104	1.53	1.31	9.29	6.96	0.77	4.15	2.02	1.16	1.58
Apr	105	1.45	1.89	9.84	7.47	0.80	4.74	1.90	1.49	1.59
Apr	106	1.45	3.71	11.62	8.71	0.82	4.40	1.99	1.29	1.56
Apr	107	1.43	3.50	12.51	8.41	0.78	5.80	1.91	1.87	1.96
Apr	108	1.35	3.98	12.10	8.68	0.80	4.53	2.02	1.37	1.83
Apr	109	1.47	3.86	12.06	8.43	0.78	3.50	2.04	1.02	1.81
Apr	110	1.49	3.38	12.48	8.70	0.81	4.59	2.15	1.35	1.85
Apr	111	1.39	3.59	12.61	8.81	0.81	4.00	2.06	1.23	1.80
Apr	112	1.30	3.73	12.47	8.72	0.80	4.68	2.09	1.47	1.85
Apr	113	1.49	3.43	12.26	8.37	0.79	3.87	2.08	1.16	1.86
Apr	114	1.53	4.13	11.77	8.71	0.81	4.40	2.09	1.42	1.81
Apr	115	1.47	3.10	11.71	7.96	0.77	3.80	2.15	1.16	1.98
Apr	116	1.42	2.98	11.76	8.14	0.79	4.45	2.28	1.28	1.86
Apr	117	1.40	3.14	12.45	8.33	0.78	4.74	2.17	1.50	1.99
Apr	118	1.43	3.32	12.90	8.17	0.75	4.09	2.22	1.28	2.09
Apr	119	1.45	3.90	12.88	8.43	0.76	5.22	2.24	1.71	2.17
Apr	120	1.39	4.12	13.42	8.67	0.77	4.58	2.42	1.35	2.16

Apr	121	1.40	4.69	13.75	9.26	0.79	5.85	2.32	1.90	2.20
May	122	1.36	5.60	14.52	9.53	0.77	4.96	2.33	1.57	2.25
May	123	1.49	5.12	15.16	9.47	0.76	6.31	2.23	2.19	2.46
May	124	1.52	5.50	14.51	9.60	0.78	5.01	2.40	1.58	2.31
May	125	1.59	5.34	14.35	9.55	0.78	4.95	2.40	1.59	2.27
May	126	1.51	4.83	13.42	9.49	0.82	4.37	2.45	1.34	2.05
May	127	1.57	4.39	13.36	8.83	0.77	4.97	2.38	1.63	2.24
May	128	1.66	4.65	13.20	9.13	0.79	5.57	2.51	1.77	2.20
May	129	1.56	4.89	13.20	9.32	0.80	5.67	2.43	1.91	2.20
May	130	1.67	4.43	13.14	8.97	0.79	4.83	2.44	1.60	2.18
May	131	1.77	5.02	13.51	9.09	0.78	5.24	2.42	1.78	2.34
May	132	1.80	4.51	13.10	8.83	0.77	5.12	2.49	1.70	2.32
May	133	1.77	4.05	12.06	8.37	0.77	5.03	2.46	1.72	2.25
May	134	1.63	3.59	12.45	8.41	0.78	4.20	2.54	1.33	2.16
May	135	1.72	4.51	12.98	8.88	0.78	4.82	2.52	1.63	2.22
May	136	1.55	5.37	14.68	9.50	0.77	6.88	2.43	2.48	2.56
May	137	1.55	6.26	15.48	9.81	0.75	5.59	2.57	1.90	2.54
May	138	1.53	6.76	16.42	10.35	0.75	6.21	2.52	2.17	2.68
May	139	1.54	6.28	16.15	10.67	0.80	5.91	2.47	2.11	2.63
May	140	1.60	6.38	15.53	10.12	0.77	5.57	2.57	1.90	2.58
May	141	1.63	6.13	15.05	10.06	0.78	5.90	2.70	1.97	2.58
May	142	1.59	5.77	15.06	9.96	0.78	4.99	2.54	1.74	2.46
May	143	1.74	6.36	15.20	10.18	0.78	5.48	2.56	1.93	2.50
May	144	1.64	6.37	14.95	10.04	0.78	3.26	2.76	0.94	2.42
May	145	1.67	6.62	14.77	10.12	0.78	4.84	2.64	1.63	2.48
May	146	1.59	5.86	15.09	9.69	0.76	6.58	2.63	2.36	2.76
May	147	1.61	6.37	14.83	9.63	0.75	4.42	2.70	1.45	2.60
May	148	1.59	6.52	14.97	9.60	0.73	4.74	2.66	1.62	2.59
May	149	1.65	6.13	15.19	9.77	0.76	4.62	2.78	1.48	2.59
May	150	1.64	6.32	15.27	10.18	0.78	5.94	2.66	2.13	2.57
May	151	1.64	6.23	15.00	10.17	0.79	5.99	2.79	2.05	2.61
May	152	2.10	6.50	16.29	11.02	0.81	6.15	2.64	2.21	2.54
Jun	153	2.22	7.45	16.73	11.41	0.81	6.22	2.73	2.19	2.68
Jun	154	2.27	7.32	16.56	11.37	0.81	4.84	2.81	1.59	2.56
Jun	155	2.36	8.00	16.91	11.60	0.80	5.75	2.65	2.08	2.67
Jun	156	2.17	7.27	16.74	11.10	0.79	6.79	2.64	2.51	2.91
Jun	157	1.95	7.27	16.58	11.01	0.79	5.69	2.78	1.98	2.79
Jun	158	1.96	7.52	16.85	11.73	0.82	5.15	2.74	1.82	2.59
Jun	159	1.94	7.74	16.85	11.83	0.82	4.88	2.90	1.58	2.56
Jun	160	1.90	8.20	16.93	11.77	0.81	5.01	2.87	1.66	2.66
Jun	161	1.80	7.80	17.07	11.42	0.78	3.97	2.94	1.22	2.62
Jun	162	1.85	7.75	17.30	11.77	0.81	5.89	2.93	1.93	2.74
Jun	163	1.84	7.59	17.07	11.51	0.80	6.01	2.79	2.14	2.77
Jun	164	1.77	7.69	16.98	11.29	0.78	6.14	2.71	2.23	2.85
Jun	165	1.83	7.79	16.31	11.18	0.79	5.37	2.77	1.89	2.74
Jun	166	1.81	7.51	16.33	10.78	0.77	3.78	2.83	1.21	2.64

Jun	167	2.02	8.29	17.18	11.87	0.80	3.94	2.97	1.19	2.53
Jun	168	1.88	8.56	17.19	11.74	0.79	4.51	3.04	1.37	2.69
Jun	169	1.84	8.99	17.62	12.61	0.83	5.58	2.89	1.89	2.73
Jun	170	1.89	8.72	17.37	11.59	0.77	5.23	2.79	1.82	2.93
Jun	171	1.82	8.32	16.83	11.63	0.80	5.07	2.83	1.74	2.75
Jun	172	1.78	8.92	17.59	11.65	0.76	4.94	2.86	1.67	2.86
Jun	173	1.84	8.59	17.26	11.68	0.78	5.35	2.97	1.73	2.86
Jun	174	1.76	8.05	17.17	12.07	0.82	4.91	2.96	1.56	2.67
Jun	175	1.90	8.56	17.48	11.77	0.78	5.16	2.82	1.77	2.82
Jun	176	1.77	8.82	17.79	11.80	0.77	4.96	2.97	1.59	2.86
Jun	177	1.87	8.06	17.74	11.45	0.77	6.78	2.87	2.36	3.14
Jun	178	1.83	8.68	17.53	11.71	0.77	4.15	2.92	1.29	2.77
Jun	179	1.74	8.70	17.59	11.37	0.75	5.15	2.91	1.69	2.98
Jun	180	1.72	8.19	17.21	11.52	0.78	5.72	2.86	1.92	2.97
Jun	181	1.73	8.54	16.83	11.08	0.75	5.78	2.73	2.08	2.98
Jul	182	1.58	9.74	18.08	12.42	0.78	4.55	2.81	1.52	2.79
Jul	183	1.30	9.46	18.55	12.61	0.79	3.75	2.81	1.22	2.72
Jul	184	1.46	9.24	18.60	12.40	0.78	4.66	2.86	1.53	2.91
Jul	185	1.53	9.30	18.20	12.29	0.78	4.67	2.90	1.50	2.90
Jul	186	1.59	9.41	18.52	12.66	0.79	5.61	2.83	1.92	2.92
Jul	187	1.65	10.13	18.04	12.89	0.80	5.16	2.84	1.73	2.73
Jul	188	1.65	10.28	18.34	13.13	0.80	5.03	2.80	1.72	2.81
Jul	189	1.80	9.71	18.30	12.92	0.80	4.35	2.83	1.40	2.73
Jul	190	1.86	9.63	18.73	12.86	0.79	3.85	2.79	1.25	2.71
Jul	191	1.83	9.45	18.58	12.42	0.78	4.61	2.80	1.49	2.85
Jul	192	1.82	9.80	18.07	12.82	0.81	4.43	2.85	1.40	2.67
Jul	193	1.85	9.97	18.27	13.02	0.81	5.22	2.57	1.92	2.76
Jul	194	1.88	10.01	18.31	12.70	0.79	4.06	2.78	1.30	2.72
Jul	195	1.77	9.51	19.02	13.15	0.81	5.18	2.75	1.73	2.83
Jul	196	1.82	9.51	17.84	12.15	0.77	4.25	2.74	1.38	2.79
Jul	197	1.71	9.67	18.30	12.63	0.79	4.49	2.73	1.50	2.72
Jul	198	1.90	9.73	18.62	13.43	0.83	4.58	2.75	1.49	2.56
Jul	199	1.80	9.58	18.86	13.34	0.82	6.25	2.53	2.30	2.84
Jul	200	1.70	10.12	19.67	13.72	0.81	6.20	2.66	2.14	2.87
Jul	201	1.67	10.00	19.62	13.74	0.81	5.83	2.73	1.94	2.87
Jul	202	1.69	9.99	19.12	13.65	0.82	5.40	2.71	1.78	2.75
Jul	203	1.91	9.87	19.22	13.06	0.79	5.51	2.59	1.90	2.87
Jul	204	1.83	10.84	19.06	13.58	0.79	4.53	2.52	1.58	2.76
Jul	205	1.74	10.07	18.76	13.39	0.81	5.26	2.44	1.89	2.71
Jul	206	1.78	9.79	18.57	13.13	0.81	5.09	2.49	1.76	2.67
Jul	207	1.84	9.50	18.79	13.06	0.81	4.55	2.68	1.43	2.63
Jul	208	1.68	10.36	19.25	13.55	0.81	3.90	2.49	1.29	2.54
Jul	209	1.88	10.40	19.26	13.62	0.81	5.18	2.58	1.73	2.63
Jul	210	1.86	10.24	19.00	13.75	0.83	5.60	2.60	1.83	2.67
Jul	211	1.77	10.15	18.74	13.25	0.81	4.37	2.65	1.31	2.62
Jul	212	1.84	9.65	19.58	13.06	0.78	6.30	2.56	2.10	2.84

Aug	213	2.21	9.65	19.39	13.34	0.81	4.99	2.46	1.66	2.66
Aug	214	2.34	9.95	18.66	13.38	0.82	4.24	2.36	1.42	2.49
Aug	215	2.25	9.73	18.41	12.77	0.79	3.82	2.57	1.10	2.47
Aug	216	2.16	9.98	18.50	13.15	0.80	3.45	2.48	1.07	2.40
Aug	217	2.02	10.22	18.86	13.69	0.82	4.16	2.42	1.30	2.39
Aug	218	2.04	10.18	19.01	13.26	0.79	3.86	2.51	1.11	2.50
Aug	219	1.86	10.00	18.86	13.31	0.80	3.76	2.35	1.20	2.41
Aug	220	1.88	9.90	18.73	13.64	0.83	4.68	2.28	1.57	2.35
Aug	221	1.83	9.46	19.03	13.29	0.81	4.69	2.36	1.46	2.42
Aug	222	1.78	10.41	19.08	13.77	0.82	3.92	2.32	1.22	2.28
Aug	223	1.79	9.95	19.08	13.89	0.84	3.88	2.30	1.20	2.34
Aug	224	1.90	10.40	19.74	13.48	0.78	5.34	2.23	1.77	2.64
Aug	225	1.87	10.01	18.83	13.68	0.83	5.62	2.22	1.88	2.46
Aug	226	1.92	10.02	19.26	13.75	0.82	4.12	2.26	1.27	2.33
Aug	227	1.78	10.28	19.17	13.40	0.79	4.37	2.32	1.27	2.47
Aug	228	1.89	10.26	18.55	13.50	0.82	2.65	2.19	0.77	2.18
Aug	229	1.78	10.34	18.53	12.99	0.79	4.40	2.16	1.41	2.42
Aug	230	1.86	9.63	17.79	13.21	0.84	5.06	2.16	1.60	2.20
Aug	231	1.80	9.48	18.28	12.75	0.80	3.71	2.15	1.11	2.18
Aug	232	1.91	9.34	18.02	12.84	0.82	5.63	1.96	1.92	2.32
Aug	233	1.89	9.38	18.17	12.80	0.81	4.90	2.09	1.53	2.28
Aug	234	1.88	9.53	17.98	12.35	0.79	4.44	2.09	1.36	2.34
Aug	235	1.85	9.63	18.19	13.20	0.83	3.75	2.08	1.11	2.10
Aug	236	1.84	10.37	18.56	12.88	0.78	4.63	2.06	1.40	2.33
Aug	237	1.98	10.19	18.47	13.22	0.81	4.35	1.97	1.33	2.18
Aug	238	1.97	10.22	18.56	13.16	0.80	4.97	1.94	1.56	2.32
Aug	239	1.81	10.28	19.07	13.47	0.81	4.40	1.93	1.33	2.19
Aug	240	1.72	9.14	18.73	12.98	0.81	5.00	1.85	1.60	2.24
Aug	241	1.72	9.52	18.60	12.84	0.80	4.37	2.01	1.22	2.12
Aug	242	1.79	9.93	18.60	13.00	0.80	4.06	1.80	1.28	2.19
Aug	243	1.90	9.46	18.53	12.96	0.81	3.95	2.01	1.05	2.11
Sep	244	1.95	8.45	16.98	12.38	0.84	3.71	1.95	0.99	1.91
Sep	245	2.08	8.67	16.44	12.07	0.83	3.36	1.82	0.96	1.78
Sep	246	2.17	8.36	16.70	12.15	0.83	4.24	1.82	1.23	1.79
Sep	247	2.19	8.60	16.43	11.80	0.81	4.45	1.75	1.30	1.94
Sep	248	2.10	8.02	15.92	11.64	0.82	3.36	1.78	0.92	1.73
Sep	249	2.22	8.03	15.85	11.52	0.82	3.42	1.70	0.98	1.71
Sep	250	2.19	7.73	15.70	11.14	0.80	3.72	1.71	1.03	1.75
Sep	251	2.20	7.73	16.18	11.59	0.82	3.67	1.65	1.04	1.73
Sep	252	2.20	7.83	15.84	11.68	0.84	3.95	1.74	1.04	1.65
Sep	253	2.20	7.99	16.23	11.80	0.83	4.42	1.70	1.19	1.69
Sep	254	2.30	7.73	16.05	11.72	0.84	3.72	1.59	1.03	1.60
Sep	255	2.27	7.93	16.24	11.90	0.84	3.90	1.61	1.06	1.58
Sep	256	2.10	7.85	16.72	12.06	0.83	4.60	1.63	1.22	1.61
Sep	257	2.11	7.91	16.32	11.80	0.83	3.99	1.58	1.05	1.66
Sep	258	2.05	7.90	16.66	12.33	0.86	3.43	1.58	0.87	1.50

Sep	259	2.17	7.53	15.45	11.09	0.81	3.28	1.53	0.85	1.60
Sep	260	2.13	7.27	15.37	11.25	0.83	2.83	1.49	0.71	1.53
Sep	261	2.20	7.77	15.36	12.06	0.88	3.25	1.44	0.83	1.31
Sep	262	2.10	7.09	15.04	11.70	0.88	3.10	1.44	0.78	1.25
Sep	263	2.25	7.57	14.84	11.12	0.83	2.72	1.45	0.64	1.39
Sep	264	2.15	7.37	14.82	11.13	0.84	2.80	1.47	0.63	1.36
Sep	265	2.16	7.84	15.86	11.95	0.86	4.14	1.35	1.08	1.38
Sep	266	2.23	8.35	15.30	11.64	0.83	2.47	1.41	0.55	1.40
Sep	267	2.16	7.93	15.64	12.15	0.87	2.92	1.39	0.66	1.26
Sep	268	2.04	7.38	15.43	11.62	0.85	3.84	1.33	0.93	1.38
Sep	269	2.07	7.59	15.04	11.60	0.86	2.28	1.28	0.51	1.17
Sep	270	2.08	7.42	15.34	11.60	0.86	2.88	1.27	0.67	1.28
Sep	271	2.11	7.82	15.09	11.61	0.85	3.10	1.26	0.71	1.23
Sep	272	2.36	7.99	16.49	12.31	0.86	3.66	1.30	0.80	1.23
Sep	273	2.08	8.03	15.70	12.19	0.87	4.17	1.14	1.04	1.28
Oct	274	2.29	6.82	14.00	10.91	0.86	4.17	1.24	0.83	1.22
Oct	275	2.28	6.52	13.37	10.79	0.87	3.06	1.25	0.52	1.05
Oct	276	2.35	6.58	13.29	10.81	0.88	3.24	1.19	0.60	0.96
Oct	277	2.35	6.43	14.10	11.01	0.87	3.29	1.18	0.58	0.98
Oct	278	2.32	6.80	13.79	11.02	0.87	2.46	1.15	0.41	0.98
Oct	279	2.43	6.76	13.78	10.95	0.86	2.20	1.09	0.36	0.95
Oct	280	2.36	5.99	13.27	10.45	0.86	3.48	1.10	0.62	0.98
Oct	281	2.40	6.56	13.09	10.71	0.87	2.44	1.09	0.40	0.89
Oct	282	2.33	6.64	13.34	10.80	0.87	2.61	1.05	0.43	0.89
Oct	283	2.27	6.75	14.37	11.16	0.87	2.61	1.04	0.43	0.85
Oct	284	2.28	6.58	13.36	10.88	0.88	2.76	0.93	0.50	0.93
Oct	285	2.46	6.33	13.03	10.56	0.87	2.61	0.96	0.44	0.88
Oct	286	2.45	5.70	12.81	10.28	0.87	1.88	0.97	0.28	0.85
Oct	287	2.33	6.41	13.13	10.62	0.87	2.59	0.94	0.41	0.79
Oct	288	2.25	6.43	13.51	10.87	0.88	2.53	0.90	0.40	0.80
Oct	289	2.42	5.51	12.31	9.97	0.86	2.01	0.90	0.30	0.92
Oct	290	2.56	5.10	11.65	9.43	0.84	2.52	0.88	0.38	0.90
Oct	291	2.32	4.62	11.30	9.59	0.89	2.19	0.86	0.33	0.73
Oct	292	2.28	4.65	11.45	9.33	0.85	2.44	0.85	0.35	0.75
Oct	293	2.37	4.32	11.24	8.66	0.81	2.66	0.84	0.38	0.98
Oct	294	2.33	4.33	11.34	9.33	0.86	2.82	0.80	0.43	0.76
Oct	295	2.42	4.96	12.11	9.95	0.88	2.38	0.78	0.34	0.64
Oct	296	2.51	4.01	11.02	9.18	0.88	2.37	0.78	0.33	0.75
Oct	297	2.28	4.95	11.58	9.57	0.86	1.94	0.74	0.28	0.75
Oct	298	2.34	4.10	11.74	9.00	0.83	2.86	0.77	0.39	0.83
Oct	299	2.37	4.32	11.49	9.38	0.87	2.51	0.72	0.34	0.71
Oct	300	2.46	4.09	11.39	9.45	0.89	2.28	0.72	0.30	0.61
Oct	301	2.43	3.95	11.29	8.83	0.84	2.41	0.64	0.34	0.79
Oct	302	2.41	3.92	10.30	8.86	0.86	1.63	0.66	0.20	0.68
Oct	303	2.47	4.32	10.64	8.98	0.85	2.68	0.66	0.34	0.65
Oct	304	2.24	4.87	11.54	9.59	0.87	2.51	0.64	0.33	0.62

Nov	305	2.33	2.59	9.44	8.13	0.85	2.38	0.64	0.29	0.72
Nov	306	2.27	2.08	9.15	8.16	0.88	2.07	0.58	0.26	0.55
Nov	307	2.23	1.50	9.39	8.01	0.87	1.83	0.59	0.21	0.53
Nov	308	2.10	1.68	8.52	7.62	0.85	1.97	0.55	0.25	0.60
Nov	309	2.09	1.62	8.33	8.10	0.91	1.92	0.56	0.23	0.42
Nov	310	2.10	2.33	8.61	8.03	0.87	1.33	0.56	0.14	0.49
Nov	311	2.11	2.55	9.01	8.11	0.87	1.68	0.53	0.19	0.58
Nov	312	2.06	2.73	9.76	8.28	0.86	1.67	0.52	0.18	0.55
Nov	313	2.16	1.79	9.22	8.18	0.89	1.57	0.50	0.17	0.48
Nov	314	2.21	1.73	9.45	8.04	0.87	1.81	0.49	0.20	0.57
Nov	315	2.09	1.91	8.98	7.61	0.83	2.03	0.49	0.22	0.64
Nov	316	2.24	2.02	8.77	7.99	0.87	1.87	0.47	0.19	0.43
Nov	317	2.17	3.56	9.31	8.19	0.84	1.88	0.48	0.19	0.59
Nov	318	2.23	3.26	10.33	8.52	0.84	1.63	0.46	0.16	0.66
Nov	319	2.21	2.78	9.60	8.14	0.85	2.12	0.46	0.22	0.61
Nov	320	2.12	1.08	7.89	7.51	0.88	1.31	0.43	0.12	0.53
Nov	321	2.07	1.11	7.52	7.51	0.89	2.05	0.41	0.21	0.42
Nov	322	2.09	1.28	7.72	7.46	0.88	1.50	0.43	0.13	0.42
Nov	323	2.10	0.90	7.38	7.29	0.87	1.07	0.41	0.09	0.49
Nov	324	2.14	0.92	7.06	7.20	0.88	2.39	0.41	0.22	0.44
Nov	325	2.15	0.44	6.99	7.09	0.88	1.84	0.41	0.16	0.43
Nov	326	2.08	0.86	7.73	7.09	0.84	1.88	0.38	0.17	0.50
Nov	327	2.15	-0.04	7.81	7.17	0.88	2.11	0.38	0.19	0.47
Nov	328	2.07	0.74	6.60	6.93	0.85	1.99	0.38	0.17	0.43
Nov	329	2.08	0.29	6.54	6.61	0.82	1.93	0.34	0.17	0.43
Nov	330	2.26	-0.26	6.30	6.80	0.88	1.95	0.33	0.18	0.38
Nov	331	2.20	-0.09	6.17	6.86	0.89	1.67	0.34	0.14	0.34
Nov	332	2.13	-0.33	6.73	6.84	0.88	1.23	0.33	0.10	0.35
Nov	333	2.23	-0.43	6.70	6.93	0.89	1.66	0.35	0.12	0.31
Nov	334	2.11	0.53	7.34	7.46	0.90	1.57	0.32	0.13	0.33
Nov	335	2.15	0.82	6.78	6.87	0.85	1.31	0.30	0.11	0.53
Dec	336	2.21	1.47	7.40	7.47	0.88	1.27	0.31	0.09	0.41
Dec	337	2.23	1.47	7.42	7.42	0.87	1.37	0.31	0.10	0.44
Dec	338	2.20	0.93	7.26	7.44	0.89	1.28	0.30	0.09	0.38
Dec	339	2.15	0.61	7.23	7.28	0.89	1.23	0.28	0.09	0.39
Dec	340	2.20	1.42	6.99	7.27	0.86	1.15	0.29	0.09	0.38
Dec	341	2.12	0.88	6.94	7.27	0.88	1.15	0.29	0.08	0.38
Dec	342	2.07	1.39	7.16	7.43	0.88	1.21	0.27	0.09	0.36
Dec	343	2.24	0.50	7.17	7.21	0.87	1.12	0.26	0.08	0.40
Dec	344	2.22	0.23	6.95	6.97	0.87	0.97	0.27	0.07	0.46
Dec	345	2.21	0.56	7.22	7.08	0.86	0.74	0.26	0.05	0.47
Dec	346	2.30	1.29	7.72	7.31	0.85	0.80	0.26	0.05	0.48
Dec	347	2.13	1.00	7.53	7.67	0.90	1.16	0.25	0.08	0.36
Dec	348	2.09	1.45	7.04	7.70	0.91	1.24	0.27	0.08	0.32
Dec	349	2.19	0.96	7.26	7.58	0.90	0.61	0.25	0.04	0.32
Dec	350	2.23	0.93	6.17	6.67	0.83	1.39	0.27	0.09	0.52

Dec	351	2.28	0.39	6.50	6.97	0.87	1.10	0.25	0.08	0.45
Dec	352	2.25	0.33	5.12	6.21	0.83	1.11	0.25	0.08	0.57
Dec	353	2.26	-0.24	5.69	6.77	0.90	0.83	0.27	0.05	0.33
Dec	354	2.30	0.30	5.75	6.63	0.86	1.22	0.27	0.08	0.43
Dec	355	2.18	0.54	5.78	6.82	0.89	1.20	0.25	0.08	0.39
Dec	356	2.13	-0.39	5.37	6.58	0.89	1.28	0.25	0.09	0.35
Dec	357	2.09	0.17	6.04	6.59	0.85	1.02	0.25	0.07	0.45
Dec	358	2.28	0.71	6.64	7.14	0.89	1.31	0.26	0.09	0.31
Dec	359	2.15	0.61	7.09	6.83	0.84	1.02	0.25	0.07	0.57
Dec	360	2.16	0.24	6.41	6.59	0.84	1.37	0.27	0.09	0.45
Dec	361	2.18	0.71	6.27	6.83	0.85	1.38	0.26	0.10	0.45
Dec	362	2.34	0.05	6.10	6.68	0.86	1.35	0.28	0.09	0.44
Dec	363	2.23	0.29	5.01	6.32	0.84	1.03	0.26	0.07	0.46
Dec	364	2.18	0.24	5.34	6.59	0.87	1.38	0.25	0.10	0.34
Dec	365	2.23	-0.46	5.14	6.25	0.85	1.14	0.26	0.08	0.48
Dec	366	2.05	-1.54	4.48	6.18	0.90	1.31	0.28	0.08	0.28

Appendix 1.2. Mean daily climate projections for 2070-2099 under the IPCC A1F1 emissions scenario

Month	Day	Total daily precipitation, mm	Minimum daily temperature, °C	Maximum daily temperature, °C	Vapour pressure (hPa)	Relative humidity, %	Sunshine hours, hr	Downward diffuse irradiation (W/m^2)	Direct irradiation (W/m^2)	Daily mean potential evapotranspiration, mm/day
Jan	1	2.57	1.05	7.31	7.36	0.88	0.78	0.26	0.05	0.45
Jan	2	2.82	1.42	8.16	7.76	0.89	0.73	0.26	0.05	0.48
Jan	3	2.90	1.59	7.61	7.43	0.86	0.62	0.26	0.04	0.58
Jan	4	2.77	1.74	8.61	8.05	0.90	0.82	0.27	0.05	0.40
Jan	5	2.82	2.31	8.39	8.16	0.91	0.82	0.27	0.06	0.44
Jan	6	2.79	2.32	9.14	8.32	0.90	1.23	0.29	0.09	0.47
Jan	7	2.86	2.13	8.19	7.80	0.87	1.13	0.29	0.08	0.55
Jan	8	2.97	1.55	7.96	7.89	0.90	1.08	0.29	0.08	0.38
Jan	9	2.83	1.62	7.56	7.62	0.89	0.95	0.29	0.08	0.43
Jan	10	2.71	1.20	8.15	7.78	0.89	0.85	0.29	0.07	0.42
Jan	11	2.77	1.12	8.12	8.03	0.93	1.07	0.31	0.08	0.31
Jan	12	2.90	1.47	7.57	7.75	0.91	0.89	0.32	0.07	0.39
Jan	13	2.79	1.78	7.94	7.71	0.88	0.84	0.31	0.07	0.52
Jan	14	2.69	2.16	8.88	8.32	0.91	0.66	0.31	0.05	0.45
Jan	15	2.88	2.45	8.68	7.78	0.84	1.35	0.34	0.11	0.69
Jan	16	2.82	2.86	8.97	8.00	0.85	1.60	0.34	0.14	0.59
Jan	17	2.83	3.27	8.82	8.03	0.85	0.72	0.33	0.06	0.63
Jan	18	2.84	3.61	8.99	8.08	0.83	0.66	0.34	0.05	0.71
Jan	19	2.74	3.32	9.00	8.48	0.89	1.34	0.36	0.12	0.54
Jan	20	2.80	3.00	9.11	8.09	0.85	1.16	0.37	0.11	0.62
Jan	21	2.82	2.44	9.21	8.20	0.88	1.33	0.39	0.12	0.61
Jan	22	2.74	1.91	8.28	7.96	0.89	1.46	0.38	0.15	0.50
Jan	23	2.75	2.18	8.96	8.10	0.88	1.05	0.41	0.09	0.49
Jan	24	2.86	2.17	8.53	7.90	0.87	1.13	0.41	0.10	0.53
Jan	25	2.85	2.44	7.80	7.57	0.85	1.11	0.41	0.10	0.57
Jan	26	2.92	2.77	7.92	7.65	0.85	0.83	0.40	0.08	0.62
Jan	27	2.92	3.08	8.69	8.39	0.89	0.85	0.42	0.08	0.48
Jan	28	2.92	2.82	8.49	8.03	0.87	1.61	0.46	0.16	0.53
Jan	29	2.95	2.22	7.98	7.74	0.87	1.00	0.44	0.11	0.56
Jan	30	2.92	3.34	8.85	8.36	0.88	1.29	0.48	0.13	0.47
Jan	31	2.89	3.68	8.78	8.20	0.85	1.35	0.47	0.15	0.65
Feb	32	2.40	2.20	7.81	7.74	0.87	1.76	0.51	0.19	0.64
Feb	33	2.17	2.60	7.78	7.76	0.86	1.88	0.53	0.20	0.59
Feb	34	2.22	2.34	8.21	7.91	0.87	1.43	0.51	0.16	0.57
Feb	35	2.33	2.42	8.37	7.76	0.85	1.52	0.53	0.17	0.58
Feb	36	2.53	2.47	8.64	7.80	0.85	2.06	0.58	0.23	0.61
Feb	37	2.63	2.65	8.35	8.11	0.88	2.16	0.57	0.25	0.49

Feb	38	2.58	2.25	8.66	8.00	0.88	2.53	0.57	0.32	0.54
Feb	39	2.58	2.35	9.10	8.03	0.86	1.67	0.58	0.20	0.64
Feb	40	2.63	2.76	9.14	7.95	0.84	1.36	0.61	0.15	0.72
Feb	41	2.72	2.63	9.18	8.12	0.86	1.64	0.61	0.21	0.67
Feb	42	2.56	2.77	8.08	7.95	0.87	1.74	0.60	0.24	0.62
Feb	43	2.69	2.70	8.83	8.06	0.87	1.69	0.65	0.21	0.64
Feb	44	2.75	2.40	8.36	7.65	0.84	2.09	0.69	0.26	0.76
Feb	45	2.67	2.51	8.46	7.95	0.87	1.68	0.69	0.22	0.66
Feb	46	2.69	1.84	8.06	7.76	0.88	1.77	0.72	0.22	0.66
Feb	47	2.62	2.04	8.29	7.76	0.86	2.41	0.75	0.33	0.64
Feb	48	2.68	2.56	8.79	8.18	0.88	1.97	0.72	0.28	0.63
Feb	49	2.65	2.36	8.26	7.79	0.86	1.51	0.78	0.19	0.71
Feb	50	2.63	2.94	8.60	7.92	0.85	1.51	0.74	0.21	0.71
Feb	51	2.73	2.57	8.67	7.57	0.82	2.57	0.78	0.39	0.88
Feb	52	2.69	2.80	8.84	7.93	0.85	1.99	0.77	0.30	0.76
Feb	53	2.57	3.04	9.76	8.44	0.87	3.00	0.82	0.47	0.71
Feb	54	2.76	2.95	9.17	8.12	0.86	2.46	0.87	0.36	0.77
Feb	55	2.66	2.53	9.09	7.95	0.85	2.33	0.88	0.34	0.74
Feb	56	2.71	2.78	8.84	8.06	0.86	1.98	0.88	0.30	0.72
Feb	57	2.66	2.37	8.96	7.93	0.85	2.50	0.96	0.37	0.77
Feb	58	2.66	2.65	8.33	7.79	0.85	1.39	0.89	0.20	0.81
Feb	59	2.71	2.69	8.97	8.02	0.86	2.53	0.97	0.40	0.82
Feb	60	2.79	3.56	10.35	8.08	0.80	3.83	0.98	0.66	1.03
Mar	61	2.81	3.84	10.35	8.48	0.83	3.43	0.98	0.59	1.00
Mar	62	2.52	4.22	10.40	8.24	0.79	2.69	1.02	0.44	1.12
Mar	63	2.39	3.39	10.38	8.10	0.81	2.44	1.03	0.40	1.12
Mar	64	2.26	3.51	10.46	8.00	0.79	2.48	1.00	0.45	1.15
Mar	65	2.20	4.24	10.84	8.38	0.80	1.83	1.12	0.27	1.29
Mar	66	2.04	4.59	11.09	8.51	0.79	1.97	1.10	0.31	1.23
Mar	67	1.99	4.41	11.10	8.54	0.80	1.72	1.11	0.29	1.27
Mar	68	1.86	4.17	10.33	8.21	0.80	2.87	1.20	0.47	1.29
Mar	69	2.03	4.08	10.70	8.15	0.78	2.96	1.12	0.55	1.29
Mar	70	1.93	3.67	10.09	7.87	0.78	2.56	1.18	0.45	1.25
Mar	71	2.00	4.22	10.13	8.31	0.82	3.48	1.19	0.68	1.09
Mar	72	2.09	3.21	10.02	8.02	0.81	2.38	1.23	0.42	1.20
Mar	73	2.14	3.45	10.12	7.97	0.80	2.45	1.21	0.46	1.19
Mar	74	2.00	3.47	9.85	7.88	0.80	2.94	1.22	0.59	1.26
Mar	75	2.15	4.53	10.74	8.55	0.81	2.02	1.27	0.36	1.22
Mar	76	2.04	4.49	10.50	8.16	0.77	3.45	1.33	0.68	1.45
Mar	77	2.04	4.26	10.78	7.98	0.76	3.42	1.30	0.71	1.51
Mar	78	2.07	3.77	10.40	7.98	0.79	3.47	1.27	0.75	1.44
Mar	79	2.07	3.89	10.48	8.23	0.81	2.32	1.43	0.39	1.37
Mar	80	2.10	3.96	10.34	7.78	0.76	2.94	1.40	0.59	1.50
Mar	81	1.93	4.12	10.79	7.85	0.75	3.37	1.46	0.67	1.58
Mar	82	1.84	4.28	11.13	8.10	0.76	4.37	1.49	0.91	1.60
Mar	83	2.12	4.16	11.34	8.14	0.76	3.40	1.43	0.75	1.55

Mar	84	2.18	4.42	10.82	8.34	0.79	2.89	1.44	0.61	1.44
Mar	85	2.00	3.75	10.97	7.78	0.75	2.92	1.52	0.61	1.65
Mar	86	1.98	3.91	10.85	7.90	0.76	3.93	1.59	0.83	1.65
Mar	87	2.12	4.33	10.63	8.26	0.79	3.10	1.57	0.67	1.49
Mar	88	2.17	4.04	10.37	8.18	0.80	3.09	1.59	0.65	1.46
Mar	89	2.11	3.64	10.50	7.66	0.75	3.90	1.63	0.86	1.66
Mar	90	1.94	3.71	10.30	7.99	0.79	3.82	1.60	0.85	1.46
Mar	91	1.79	4.22	12.67	8.82	0.79	4.34	1.54	1.21	1.53
Apr	92	1.47	4.78	13.15	8.64	0.74	4.58	1.56	1.35	1.79
Apr	93	1.54	4.27	12.95	8.53	0.75	4.43	1.60	1.29	1.81
Apr	94	1.45	4.58	12.90	8.76	0.77	4.10	1.74	1.13	1.77
Apr	95	1.38	4.97	12.71	8.78	0.76	3.88	1.78	1.04	1.75
Apr	96	1.55	4.43	12.75	8.72	0.77	4.00	1.80	1.07	1.80
Apr	97	1.49	5.23	13.40	9.29	0.79	4.77	1.69	1.45	1.76
Apr	98	1.64	5.23	13.91	9.41	0.78	4.47	1.80	1.30	1.88
Apr	99	1.55	5.22	14.02	9.39	0.78	3.47	1.89	0.91	1.83
Apr	100	1.67	5.01	13.91	9.43	0.79	5.01	1.82	1.48	1.88
Apr	101	1.57	5.07	13.30	9.16	0.78	3.92	1.92	1.10	1.84
Apr	102	1.68	5.58	13.54	9.47	0.79	4.53	1.88	1.36	1.87
Apr	103	1.73	5.14	13.55	9.38	0.79	4.65	1.98	1.34	1.87
Apr	104	1.60	4.28	12.99	8.80	0.78	3.82	1.92	1.11	1.88
Apr	105	1.51	4.79	13.27	9.29	0.80	4.77	2.03	1.36	1.85
Apr	106	1.65	6.23	14.45	9.48	0.75	4.23	2.03	1.23	2.10
Apr	107	1.68	6.16	14.58	9.57	0.75	4.07	1.84	1.34	2.14
Apr	108	1.73	6.02	14.78	9.67	0.76	5.88	2.02	1.84	2.28
Apr	109	1.60	5.61	15.06	9.69	0.77	5.14	2.07	1.56	2.22
Apr	110	1.52	5.99	14.59	9.48	0.75	4.38	2.03	1.34	2.18
Apr	111	1.76	6.04	14.82	9.61	0.75	4.28	2.04	1.36	2.18
Apr	112	1.68	6.28	15.39	9.98	0.76	5.24	2.10	1.65	2.28
Apr	113	1.75	5.57	15.39	9.48	0.74	5.60	2.02	1.86	2.42
Apr	114	1.59	6.50	14.93	9.64	0.74	5.23	2.16	1.65	2.44
Apr	115	1.71	6.98	14.85	9.93	0.75	5.14	2.05	1.73	2.36
Apr	116	1.56	6.98	15.53	10.21	0.76	5.06	2.20	1.59	2.38
Apr	117	1.64	6.81	15.30	10.08	0.76	5.53	2.23	1.78	2.41
Apr	118	1.64	6.17	14.81	9.98	0.78	3.18	2.28	0.90	2.16
Apr	119	1.57	6.04	15.12	10.16	0.79	5.02	2.26	1.60	2.24
Apr	120	1.65	6.31	15.18	9.94	0.76	5.23	2.22	1.73	2.34
Apr	121	1.81	7.35	16.04	10.51	0.76	6.06	2.18	2.10	2.49
May	122	1.69	8.23	16.77	10.99	0.76	6.72	2.29	2.26	2.62
May	123	1.73	8.30	17.23	11.40	0.77	7.20	2.27	2.47	2.73
May	124	1.69	8.69	17.37	11.76	0.78	5.24	2.38	1.69	2.61
May	125	1.68	8.74	17.24	11.70	0.78	5.86	2.32	1.96	2.73
May	126	1.56	9.16	17.37	10.93	0.71	5.23	2.50	1.62	2.87
May	127	1.70	8.45	16.57	11.02	0.75	5.97	2.29	2.08	2.81
May	128	1.65	8.60	16.66	11.00	0.75	5.72	2.34	1.98	2.78
May	129	1.51	8.53	16.71	10.91	0.74	5.24	2.51	1.68	2.75

May	130	1.46	7.51	16.74	10.63	0.75	5.67	2.56	1.81	2.77
May	131	1.69	7.21	16.65	10.74	0.76	6.19	2.42	2.14	2.73
May	132	1.68	7.43	16.19	10.47	0.75	6.73	2.38	2.38	2.70
May	133	1.70	7.67	16.20	10.90	0.78	5.76	2.45	2.00	2.61
May	134	1.77	7.26	16.88	11.13	0.79	5.99	2.57	2.00	2.64
May	135	1.57	8.15	16.32	10.96	0.77	6.50	2.40	2.34	2.73
May	136	1.62	8.87	17.48	11.65	0.77	6.23	2.58	2.08	2.77
May	137	1.66	9.10	17.80	11.64	0.75	6.21	2.61	2.09	2.91
May	138	1.63	9.04	18.41	11.48	0.73	6.13	2.58	2.11	3.16
May	139	1.61	8.58	18.07	11.49	0.75	6.48	2.56	2.27	3.08
May	140	1.58	9.09	18.06	11.79	0.76	5.93	2.63	2.00	2.96
May	141	1.40	9.41	18.22	11.67	0.73	6.36	2.48	2.29	3.07
May	142	1.56	9.91	18.56	12.12	0.74	4.51	2.81	1.33	2.88
May	143	1.70	9.52	17.96	11.82	0.75	6.46	2.54	2.32	3.11
May	144	1.55	9.17	17.91	11.50	0.74	5.39	2.65	1.86	2.98
May	145	1.70	9.07	17.69	11.46	0.74	5.30	2.71	1.79	2.94
May	146	1.67	8.95	17.67	11.87	0.77	5.23	2.64	1.81	2.85
May	147	1.60	8.64	18.33	11.58	0.75	7.42	2.58	2.72	3.17
May	148	1.51	9.01	17.78	11.80	0.77	5.28	2.70	1.80	2.88
May	149	1.57	9.56	18.21	12.36	0.78	6.90	2.62	2.48	3.00
May	150	1.52	9.07	18.22	11.67	0.75	6.02	2.74	2.05	3.12
May	151	1.66	9.46	18.98	12.12	0.75	7.11	2.72	2.52	3.24
May	152	1.55	10.56	20.64	13.28	0.75	6.44	2.75	2.24	3.31
Jun	153	1.70	11.03	21.67	13.45	0.72	6.49	2.83	2.21	3.56
Jun	154	1.58	10.77	21.04	13.68	0.75	5.83	2.79	1.99	3.42
Jun	155	1.51	10.93	21.18	13.43	0.73	6.39	2.76	2.24	3.57
Jun	156	1.48	11.10	22.29	13.99	0.73	7.04	2.71	2.53	3.63
Jun	157	1.36	10.97	21.51	13.64	0.73	6.41	2.84	2.20	3.58
Jun	158	1.62	10.91	22.22	13.61	0.71	7.09	2.80	2.51	3.79
Jun	159	1.44	11.25	22.01	13.89	0.73	6.69	2.80	2.36	3.65
Jun	160	1.44	11.25	21.72	13.71	0.73	5.59	2.98	1.79	3.56
Jun	161	1.47	11.52	22.07	14.05	0.73	5.92	2.62	2.23	3.67
Jun	162	1.47	11.50	21.27	14.17	0.75	5.45	2.84	1.88	3.42
Jun	163	1.46	11.07	21.60	13.99	0.75	6.50	2.92	2.20	3.63
Jun	164	1.39	11.72	22.29	14.13	0.73	6.22	2.86	2.14	3.61
Jun	165	1.44	11.51	22.21	14.06	0.73	6.86	2.75	2.48	3.72
Jun	166	1.44	11.54	22.36	14.55	0.75	4.88	2.88	1.62	3.44
Jun	167	1.50	12.15	21.80	14.62	0.75	4.03	2.93	1.27	3.34
Jun	168	1.40	12.53	21.38	14.05	0.72	5.44	2.93	1.80	3.69
Jun	169	1.48	12.03	22.01	13.63	0.70	6.08	3.04	1.95	3.89
Jun	170	1.45	11.70	21.35	13.64	0.72	7.83	2.75	2.88	3.91
Jun	171	1.59	12.20	22.25	14.30	0.73	5.91	2.79	2.10	3.78
Jun	172	1.56	12.33	22.34	14.60	0.73	6.54	2.85	2.29	3.76
Jun	173	1.49	11.86	22.63	14.36	0.72	5.65	2.93	1.89	3.72
Jun	174	1.44	12.68	22.00	13.93	0.70	5.12	2.99	1.64	3.63
Jun	175	1.46	12.57	22.48	14.34	0.71	6.01	2.83	2.10	3.80

Jun	176	1.49	12.45	22.56	14.71	0.73	7.01	2.96	2.38	3.78
Jun	177	1.45	12.00	21.87	14.60	0.75	6.12	2.87	2.11	3.61
Jun	178	1.40	11.85	21.75	14.02	0.73	5.89	2.84	2.06	3.75
Jun	179	1.41	12.27	22.37	14.99	0.75	6.17	2.79	2.17	3.59
Jun	180	1.41	12.98	22.04	14.67	0.73	6.55	2.71	2.41	3.75
Jun	181	1.46	12.46	22.05	14.71	0.74	5.11	2.86	1.70	3.58
Jul	182	1.55	14.71	23.71	16.66	0.74	6.06	2.79	2.13	3.69
Jul	183	1.51	15.37	24.55	17.77	0.76	7.10	2.76	2.57	3.96
Jul	184	1.63	15.61	24.89	17.71	0.74	6.00	2.78	2.11	3.92
Jul	185	1.45	15.59	24.55	17.58	0.75	4.90	2.91	1.57	3.78
Jul	186	1.52	15.14	24.60	17.84	0.77	7.74	2.82	2.72	4.00
Jul	187	1.46	14.75	24.54	17.38	0.75	8.21	2.54	3.12	4.05
Jul	188	1.53	14.99	24.45	17.49	0.76	6.56	2.82	2.28	3.84
Jul	189	1.55	14.69	24.18	17.39	0.76	6.11	2.74	2.16	3.74
Jul	190	1.53	15.11	24.21	17.17	0.75	6.69	2.68	2.42	3.91
Jul	191	1.55	14.96	24.35	17.36	0.76	5.74	2.90	1.86	3.66
Jul	192	1.58	15.10	24.54	17.28	0.74	6.87	2.67	2.49	3.92
Jul	193	1.70	14.91	24.93	17.53	0.75	7.24	2.73	2.57	4.02
Jul	194	1.55	14.86	24.48	17.54	0.76	7.56	2.64	2.76	3.97
Jul	195	1.53	14.39	24.34	17.44	0.77	6.79	2.76	2.35	3.75
Jul	196	1.57	14.30	24.37	16.64	0.73	6.59	2.66	2.35	3.85
Jul	197	1.64	15.04	24.85	18.12	0.78	7.99	2.58	2.93	3.82
Jul	198	1.54	15.32	24.47	17.70	0.76	5.38	2.86	1.70	3.55
Jul	199	1.61	15.10	24.19	17.35	0.76	5.22	2.72	1.72	3.53
Jul	200	1.54	15.34	24.20	17.28	0.75	5.92	2.69	2.03	3.59
Jul	201	1.52	14.17	25.07	17.41	0.76	7.02	2.52	2.57	3.81
Jul	202	1.65	15.05	23.93	17.69	0.78	5.42	2.65	1.83	3.45
Jul	203	1.60	14.97	23.96	17.27	0.76	5.35	2.64	1.79	3.48
Jul	204	1.51	14.35	24.24	16.93	0.75	5.26	2.54	1.83	3.56
Jul	205	1.47	15.07	24.17	17.13	0.74	6.72	2.40	2.49	3.82
Jul	206	1.48	14.69	24.38	17.39	0.76	6.49	2.56	2.28	3.69
Jul	207	1.55	15.15	23.87	16.98	0.75	5.00	2.68	1.58	3.46
Jul	208	1.67	14.54	24.68	17.15	0.75	5.41	2.56	1.82	3.51
Jul	209	1.62	14.64	24.34	17.11	0.75	5.58	2.53	1.88	3.50
Jul	210	1.50	14.75	24.54	17.33	0.75	5.98	2.44	2.10	3.57
Jul	211	1.62	14.80	24.83	17.03	0.73	5.65	2.57	1.86	3.57
Jul	212	1.68	15.06	24.58	17.58	0.76	6.06	2.53	2.02	3.45
Aug	213	1.50	14.49	24.50	17.40	0.76	5.35	2.47	1.80	3.38
Aug	214	1.65	13.97	24.34	17.03	0.77	8.15	2.34	2.92	3.69
Aug	215	1.49	14.71	24.19	17.37	0.77	6.69	2.43	2.28	3.46
Aug	216	1.62	14.75	24.32	16.95	0.74	5.18	2.49	1.65	3.40
Aug	217	1.62	15.27	24.07	17.56	0.77	4.77	2.39	1.55	3.20
Aug	218	1.61	14.72	24.21	17.11	0.75	7.20	2.30	2.53	3.52
Aug	219	1.56	14.62	23.89	17.05	0.76	4.91	2.37	1.62	3.16
Aug	220	1.57	14.28	23.41	16.57	0.75	5.03	2.45	1.56	3.17
Aug	221	1.54	14.14	23.77	17.00	0.77	6.07	2.38	1.98	3.20

Aug	222	1.57	14.16	23.32	16.26	0.75	5.45	2.38	1.71	3.26
Aug	223	1.60	13.56	23.40	16.71	0.78	7.04	2.18	2.45	3.22
Aug	224	1.55	13.66	23.44	16.93	0.79	5.29	2.34	1.69	2.99
Aug	225	1.67	14.14	24.24	17.01	0.76	7.31	2.23	2.46	3.23
Aug	226	1.56	13.84	24.28	16.45	0.74	5.96	2.27	1.93	3.29
Aug	227	1.56	14.24	23.70	16.99	0.77	4.91	2.31	1.49	2.97
Aug	228	1.71	13.61	23.18	16.31	0.77	5.87	2.17	1.94	3.13
Aug	229	1.57	13.95	22.70	15.93	0.75	6.20	2.14	2.04	3.11
Aug	230	1.47	13.65	22.93	16.18	0.77	4.68	2.29	1.36	2.92
Aug	231	1.54	14.10	23.19	16.47	0.76	5.63	2.14	1.79	3.06
Aug	232	1.41	14.33	23.54	17.01	0.78	6.36	2.03	2.11	3.02
Aug	233	1.50	14.14	22.90	16.94	0.79	5.05	2.10	1.57	2.79
Aug	234	1.67	14.20	22.98	17.04	0.79	5.07	2.05	1.61	2.74
Aug	235	1.52	14.47	23.20	17.04	0.78	7.02	1.95	2.34	3.02
Aug	236	1.57	13.69	22.95	16.33	0.77	6.11	1.98	1.97	2.88
Aug	237	1.45	14.41	23.11	16.81	0.77	5.27	2.05	1.58	2.78
Aug	238	1.51	13.62	23.01	16.29	0.77	5.40	1.94	1.70	2.87
Aug	239	1.65	13.98	23.18	16.39	0.76	5.82	1.91	1.85	2.91
Aug	240	1.55	14.34	22.89	16.70	0.78	5.96	1.89	1.90	2.74
Aug	241	1.48	14.58	22.91	17.14	0.79	5.48	1.92	1.69	2.70
Aug	242	1.51	13.99	23.02	16.78	0.79	5.04	1.95	1.48	2.70
Aug	243	1.45	13.64	22.99	16.36	0.77	6.36	1.82	2.01	2.84
Sep	244	1.84	12.67	21.98	15.59	0.79	3.98	1.91	1.12	2.52
Sep	245	1.94	12.47	21.65	15.77	0.81	3.88	1.86	1.10	2.28
Sep	246	2.02	12.29	21.78	15.62	0.80	5.28	1.76	1.62	2.42
Sep	247	2.10	12.01	21.37	15.52	0.81	6.00	1.64	1.90	2.33
Sep	248	2.13	12.42	21.69	15.67	0.80	4.79	1.77	1.39	2.23
Sep	249	2.03	12.43	21.87	15.97	0.81	5.05	1.75	1.46	2.27
Sep	250	2.05	12.37	21.99	15.88	0.81	5.89	1.61	1.82	2.35
Sep	251	2.22	12.87	22.25	16.33	0.81	3.38	1.68	0.92	2.18
Sep	252	2.05	13.21	21.93	15.81	0.78	3.31	1.71	0.88	2.27
Sep	253	2.23	12.33	21.60	15.89	0.82	5.27	1.58	1.56	2.21
Sep	254	2.24	12.33	21.72	15.67	0.81	5.38	1.58	1.56	2.21
Sep	255	2.11	12.40	21.91	16.12	0.82	5.22	1.57	1.50	2.13
Sep	256	2.09	12.30	21.85	15.53	0.79	4.75	1.57	1.31	2.23
Sep	257	2.08	12.76	21.74	15.43	0.78	4.58	1.50	1.30	2.35
Sep	258	1.99	13.35	22.13	16.08	0.79	4.39	1.52	1.20	2.31
Sep	259	2.01	12.15	21.08	15.64	0.83	4.04	1.49	1.09	2.04
Sep	260	2.10	12.29	20.21	15.33	0.83	4.55	1.51	1.19	1.91
Sep	261	2.06	11.00	20.35	15.15	0.85	5.05	1.40	1.41	1.82
Sep	262	2.12	11.92	19.72	15.26	0.85	4.19	1.45	1.09	1.69
Sep	263	2.12	11.61	20.15	14.74	0.81	4.21	1.35	1.15	1.90
Sep	264	2.30	11.03	20.19	14.79	0.83	3.75	1.39	0.95	1.77
Sep	265	2.09	11.99	20.14	15.47	0.84	4.27	1.33	1.13	1.64
Sep	266	1.97	11.54	19.86	15.03	0.84	4.02	1.37	1.00	1.62
Sep	267	2.09	11.19	19.52	14.64	0.83	4.52	1.24	1.21	1.63

Sep	268	1.96	11.86	20.15	14.64	0.80	3.74	1.24	0.97	1.74
Sep	269	2.12	11.89	20.44	15.19	0.82	4.04	1.33	0.96	1.69
Sep	270	2.16	11.85	19.60	14.85	0.83	3.79	1.29	0.90	1.67
Sep	271	1.95	11.56	20.37	15.07	0.83	4.02	1.23	0.98	1.62
Sep	272	2.14	11.51	20.00	14.95	0.83	4.45	1.21	1.09	1.57
Sep	273	2.04	11.28	20.38	15.14	0.84	4.21	1.15	1.03	1.67
Oct	274	2.35	10.18	17.94	13.59	0.84	3.92	1.20	0.81	1.52
Oct	275	2.75	10.77	17.42	13.54	0.84	3.21	1.19	0.59	1.35
Oct	276	2.57	10.17	17.07	13.18	0.84	2.57	1.23	0.42	1.34
Oct	277	2.79	10.66	17.46	13.59	0.84	3.37	1.18	0.59	1.29
Oct	278	2.69	11.46	17.09	13.52	0.82	2.64	1.11	0.46	1.29
Oct	279	2.68	10.60	17.42	13.82	0.86	2.17	1.12	0.35	1.20
Oct	280	2.52	10.97	17.55	14.09	0.86	3.28	1.11	0.57	1.09
Oct	281	2.66	10.78	17.40	13.81	0.85	2.56	1.07	0.43	1.21
Oct	282	2.64	10.62	17.38	13.16	0.82	3.13	1.08	0.52	1.36
Oct	283	2.60	10.57	17.64	13.79	0.85	3.15	1.05	0.52	1.21
Oct	284	2.50	10.65	17.41	13.13	0.82	2.24	0.92	0.39	1.44
Oct	285	2.45	10.46	17.27	13.45	0.84	3.27	0.99	0.54	1.24
Oct	286	2.61	10.36	17.09	13.08	0.83	2.43	0.93	0.41	1.24
Oct	287	2.46	10.37	17.70	13.33	0.82	3.28	0.92	0.56	1.18
Oct	288	2.43	10.06	17.50	13.35	0.84	2.97	0.90	0.49	1.10
Oct	289	2.63	9.34	16.10	12.56	0.85	2.96	0.89	0.48	1.13
Oct	290	2.58	9.16	15.45	12.60	0.87	2.53	0.91	0.37	0.96
Oct	291	2.38	8.77	16.23	12.64	0.86	3.60	0.88	0.57	1.04
Oct	292	2.46	8.28	14.90	11.94	0.86	2.24	0.86	0.31	0.98
Oct	293	2.56	8.39	14.97	12.31	0.88	2.30	0.79	0.36	0.79
Oct	294	2.48	9.07	15.12	12.28	0.86	2.99	0.82	0.44	0.90
Oct	295	2.51	8.43	15.81	12.61	0.88	3.03	0.78	0.46	0.90
Oct	296	2.74	8.46	14.79	11.98	0.86	2.29	0.78	0.32	0.92
Oct	297	2.54	7.99	15.54	12.21	0.87	2.41	0.76	0.32	0.86
Oct	298	2.43	8.84	15.46	12.13	0.85	2.88	0.76	0.39	0.84
Oct	299	2.59	8.80	15.10	12.05	0.86	1.93	0.71	0.26	0.82
Oct	300	2.55	8.82	15.39	12.47	0.87	1.80	0.72	0.22	0.77
Oct	301	2.61	8.77	15.59	12.21	0.85	2.68	0.70	0.35	0.77
Oct	302	2.62	8.75	15.01	11.95	0.85	1.96	0.66	0.26	0.87
Oct	303	2.54	8.58	14.80	12.20	0.88	1.59	0.64	0.20	0.70
Oct	304	2.47	8.87	15.75	12.60	0.87	1.76	0.62	0.22	0.80
Nov	305	2.68	7.74	14.28	11.17	0.84	2.52	0.62	0.32	0.98
Nov	306	2.73	7.34	13.82	10.66	0.83	1.24	0.59	0.14	0.97
Nov	307	2.54	7.29	13.66	10.71	0.84	1.74	0.61	0.20	0.92
Nov	308	2.75	7.53	13.82	10.65	0.82	1.03	0.54	0.12	1.01
Nov	309	2.65	7.16	13.72	10.85	0.85	1.46	0.53	0.17	0.85
Nov	310	2.50	6.34	13.59	10.76	0.87	1.70	0.54	0.20	0.73
Nov	311	2.61	6.78	13.44	10.79	0.87	1.80	0.53	0.21	0.67
Nov	312	2.67	6.66	13.30	10.44	0.84	2.45	0.54	0.28	0.71
Nov	313	2.77	6.15	12.30	10.36	0.88	1.73	0.54	0.17	0.62

Nov	314	2.57	5.89	12.55	10.32	0.88	2.04	0.51	0.22	0.61
Nov	315	2.59	6.89	12.90	10.67	0.87	2.43	0.50	0.26	0.59
Nov	316	2.58	6.62	12.31	10.38	0.87	1.81	0.46	0.20	0.65
Nov	317	2.46	6.61	13.22	10.52	0.86	1.87	0.48	0.19	0.66
Nov	318	2.58	7.82	13.69	10.94	0.84	1.92	0.45	0.20	0.71
Nov	319	2.78	7.48	14.18	11.15	0.85	1.92	0.44	0.20	0.71
Nov	320	2.59	6.24	12.44	10.10	0.85	1.53	0.44	0.15	0.88
Nov	321	2.66	5.79	11.47	9.90	0.87	1.37	0.41	0.13	0.62
Nov	322	2.69	6.21	12.13	9.86	0.82	1.26	0.40	0.12	0.65
Nov	323	2.51	5.85	11.43	9.95	0.88	1.50	0.40	0.14	0.58
Nov	324	2.73	5.38	11.33	9.53	0.86	1.27	0.39	0.11	0.67
Nov	325	2.50	4.96	11.53	9.88	0.90	1.45	0.39	0.13	0.54
Nov	326	2.59	5.63	11.57	9.96	0.87	1.89	0.37	0.18	0.53
Nov	327	2.59	5.68	12.43	10.09	0.87	1.67	0.38	0.14	0.68
Nov	328	2.63	5.88	11.90	9.77	0.85	1.57	0.38	0.13	0.71
Nov	329	2.58	5.58	11.89	9.96	0.87	1.27	0.36	0.10	0.53
Nov	330	2.68	5.35	12.01	9.54	0.83	1.22	0.33	0.10	0.67
Nov	331	2.68	5.49	12.39	10.33	0.89	1.46	0.34	0.12	0.50
Nov	332	2.57	5.64	11.96	9.75	0.85	1.27	0.34	0.09	0.67
Nov	333	2.65	5.62	10.86	9.54	0.86	1.05	0.32	0.09	0.61
Nov	334	2.62	5.18	10.64	9.66	0.90	1.62	0.32	0.13	0.42
Nov	335	2.59	4.52	10.29	9.08	0.87	1.76	0.32	0.13	0.47
Dec	336	2.62	4.18	10.50	8.94	0.86	1.27	0.30	0.10	0.56
Dec	337	2.73	3.67	10.74	9.14	0.88	0.91	0.30	0.07	0.56
Dec	338	2.78	4.01	10.71	8.89	0.86	1.22	0.30	0.09	0.64
Dec	339	2.71	4.09	10.87	9.10	0.87	1.15	0.29	0.09	0.62
Dec	340	2.91	3.88	10.07	8.81	0.87	1.27	0.29	0.09	0.50
Dec	341	2.91	3.85	10.63	8.91	0.86	0.99	0.29	0.07	0.62
Dec	342	2.74	3.73	10.44	8.79	0.87	1.07	0.28	0.07	0.57
Dec	343	2.91	3.36	10.05	8.78	0.88	1.32	0.29	0.09	0.52
Dec	344	2.88	2.93	10.09	8.58	0.87	1.17	0.27	0.08	0.54
Dec	345	2.88	3.30	9.97	8.73	0.88	1.28	0.26	0.09	0.45
Dec	346	2.93	4.03	10.07	8.79	0.87	0.85	0.27	0.05	0.59
Dec	347	3.03	4.16	10.50	9.15	0.89	1.05	0.26	0.07	0.43
Dec	348	2.85	3.98	10.38	8.83	0.86	1.50	0.27	0.10	0.54
Dec	349	2.78	4.90	11.06	9.49	0.88	1.49	0.26	0.11	0.52
Dec	350	2.78	3.91	9.60	8.64	0.86	0.90	0.26	0.06	0.66
Dec	351	2.88	3.53	9.98	8.60	0.86	1.21	0.26	0.08	0.59
Dec	352	2.91	3.54	9.58	8.45	0.86	0.92	0.25	0.06	0.63
Dec	353	2.96	3.40	9.74	8.41	0.85	1.33	0.25	0.10	0.61
Dec	354	2.92	3.83	10.17	8.65	0.85	1.23	0.26	0.08	0.63
Dec	355	2.99	4.03	10.46	8.73	0.84	0.71	0.25	0.05	0.76
Dec	356	3.00	3.85	9.26	8.58	0.87	1.43	0.26	0.10	0.54
Dec	357	2.75	3.72	9.96	8.66	0.87	1.09	0.25	0.07	0.55
Dec	358	2.86	3.77	9.87	8.49	0.85	0.98	0.24	0.07	0.64
Dec	359	2.94	3.09	10.05	8.42	0.86	1.35	0.26	0.09	0.56

Dec	360	2.92	3.07	9.12	8.47	0.89	1.21	0.26	0.08	0.50
Dec	361	2.83	2.59	8.91	8.15	0.87	1.07	0.26	0.07	0.56
Dec	362	2.95	3.40	9.91	8.76	0.89	0.68	0.26	0.04	0.50
Dec	363	2.89	3.68	10.08	8.67	0.87	1.21	0.26	0.08	0.64
Dec	364	2.88	4.07	10.20	8.90	0.86	1.44	0.27	0.10	0.52
Dec	365	2.94	2.92	9.54	8.25	0.86	1.50	0.26	0.11	0.53
Dec	366	2.57	1.05	7.31	7.36	0.88	0.78	0.26	0.05	0.45

Appendix 2. Meteorological Data - JHI, Invergowrie, Dundee - Daily Values

2011

Date	Air Max °C	Air Min °C	Rain mm	Wind Direction	Wind Speed knots
1-Jan	3.1	0.8	tr	0	0
2-Jan	3.0	0.3	0.0	0	0
3-Jan	3.8	-0.5	0.3	310	2
4-Jan	5.3	-0.6	4.2	180	2
5-Jan	3.9	-1.2	2.6	270	2
6-Jan	1.9	-1.0	tr	320	8
7-Jan	1.0	-6.8	2.3	300	2
8-Jan	2.9	-6.2	1.7	320	8
9-Jan	3.7	-4.9	0.4	290	2
10-Jan	4.2	-4.1	11.6	0	0
11-Jan	4.2	1.3	3.9	360	8
12-Jan	3.1	-2.2	4.3	30	2
13-Jan	6.7	-0.4	4.4	180	8
14-Jan	8.9	1.2	3.7	170	2
15-Jan	11.0	3.0	23.2	150	8
16-Jan	11.0	2.5	0.1	150	20
17-Jan	7.3	2.4	0.0	170	10
18-Jan	5.0	-1.5	0.0	0	0
19-Jan	5.7	0.4	0.0	180	7
20-Jan	7.6	-3.2	0.0	170	2
21-Jan	7.6	-3.7	0.0	180	2
22-Jan	6.5	-2.3	0.0	240	2
23-Jan	6.7	1.3	0.2	250	2
24-Jan	9.0	-0.2	0.0	180	8
25-Jan	9.0	1.3	0.0	0	0
26-Jan	6.0	1.5	0.6	300	10
27-Jan	6.1	0.8	tr	0	0
28-Jan	3.8	0.1	0.0	0	0
29-Jan	4.7	-2.5	0.0	0	0
30-Jan	5.2	-2.0	0.1	0	0
31-Jan	8.6	-2.3	0.0	150	2
Average	**5.7**	**-0.9**	**2.3**		**3.8**

Date	Air Max °C	Air Min °C	Rain mm	Wind Direction	Wind Speed knots
1-Feb	9.0	4.2	2.8	180	8
2-Feb	10.9	2.1	5.0	150	16
3-Feb	7.5	0.3	9.8	170	14
4-Feb	8.1	1.2	7.3	160	12
5-Feb	10.1	2.1	tr	240	5
6-Feb	5.8	0.3	15.8	0	0
7-Feb	5.4	0.9	5.1	310	12
8-Feb	4.6	0.3	1.7	0	0
9-Feb	5.2	0.2	3.7	260	4
10-Feb	7.8	0.9	0.2	140	2
11-Feb	5.2	-1.4	15.2	0	0
12-Feb	7.0	2.5	2.2	0	0

13-Feb	6.9	0.6	1.8	270	8
14-Feb	5.8	0.6	2.2	0	0
15-Feb	6.2	-0.8	6.6	360	12
16-Feb	6.2	3.0	6.0	20	8
17-Feb	5.2	0.2	5.2	250	2
18-Feb	5.4	1.6	6.7	30	8
19-Feb	5.1	0.7	2.3	150	12
20-Feb	5.0	2.1	0.0	120	4
21-Feb	3.9	2.3	0.4	60	2
22-Feb	7.3	2.0	8.6	0	0
23-Feb	10.8	3.0	0.6	360	2
24-Feb	13.0	5.9	1.4	140	10
25-Feb	13.0	8.1	1.6	160	12
26-Feb	13.0	5.0	0.0	0	0
27-Feb	13.0	0.5	0.0	130	4
28-Feb	9.0	-0.4	0.0	0	0
29-Feb					
Average	**7.7**	**1.7**	**4.2**		**5.6**

1-Mar	11.6	0.6	0.0	0	0
2-Mar	8.2	-0.2	tr	150	6
3-Mar	6.7	2.3	0.1	0	0
4-Mar	11.7	4.1	0.0	0	0
5-Mar	7.1	5.1	0.0	120	2
6-Mar	6.0	3.1	0.0	210	9
7-Mar	8.7	0.1	0.0	150	7
8-Mar	9.1	3.7	0.2	140	26
9-Mar	7.1	0.7	2.1	180	12
10-Mar	8.0	1.9	tr	180	30
11-Mar	7.0	-0.3	5.2	150	17
12-Mar	7.3	0.7	13.4	330	8
13-Mar	7.0	0.5	3.2	310	2
14-Mar	5.7	-0.3	0.3	330	12
15-Mar	5.7	3.3	18.9	360	5
16-Mar	7.2	-1.4	1.1	170	2
17-Mar	10.2	-1.0	tr	170	2
18-Mar	9.7	-2.4	0.0	130	2
19-Mar	10.0	-2.5	0.0	210	2
20-Mar	11.9	2.3	0.1	210	5
21-Mar	14.7	4.8	0.0	160	18
22-Mar	15.3	7.6	0.0	180	14
23-Mar	15.7	2.4	0.0	0	0
24-Mar	14.8	3.1	0.0	130	4
25-Mar	12.0	0.9	0.9	110	2
26-Mar	12.0	5.5	0.0	0	0
27-Mar	12.7	1.1	0.3	0	0
28-Mar	10.9	0.4	0.0	0	0
29-Mar	11.4	4.6	2.8	0	0
30-Mar	9.7	6.0	11.5	310	2
31-Mar	13.4	3.3	0.5	20	6
Average	**10.0**	**1.9**	**2.2**		**6.3**

1-Apr	12.9	5.9	tr	140	10
2-Apr	13.5	6.2	0.0	150	15
3-Apr	12.9	3.1	0.0	150	12
4-Apr	14.8	4.9	1.3	130	14
5-Apr	16.6	6.8	0.0	160	22
6-Apr	17.3	13.4	0.8	150	15
7-Apr	14.2	6.2	0.0	170	12
8-Apr	20.0	6.9	0.0	140	8
9-Apr	20.1	9.7	0.0	30	7
10-Apr	20.9	5.5	0.0	150	2
11-Apr	15.0	5.1	0.1	150	10
12-Apr	13.6	2.7	0.2	200	13
13-Apr	13.2	4.3	tr	140	11
14-Apr	16.4	7.9	0.0	160	10
15-Apr	14.1	6.6	0.0	170	2
16-Apr	15.1	5.6	0.0	240	10
17-Apr	18.7	4.9	0.0	240	8
18-Apr	15.7	5.0	0.0	0	0
19-Apr	17.9	6.6	0.0	0	0
20-Apr	15.4	6.2	0.0	0	0
21-Apr	13.0	6.9	0.0	0	0
22-Apr	13.9	5.5	tr	360	2
23-Apr	13.9	7.7	7.4	0	0
24-Apr	15.8	3.0	0.0	0	0
25-Apr	15.4	3.0	0.0	230	5
26-Apr	13.5	3.7	0.0	0	0
27-Apr	13.1	2.1	tr	0	0
28-Apr	14.0	3.4	0.0	70	2
29-Apr	15.9	4.1	0.0	280	6
30-Apr	13.8	4.0	0.0	120	7
Average	**15.4**	**5.6**	**0.4**		**6.8**
1-May	15.7	2.8	0.0	130	8
2-May	13.0	2.4	0.0	360	6
3-May	12.3	3.2	0.0	0	0
4-May	13.2	0.7	0.0	30	2
5-May	15.2	6.3	4.8	20	4
6-May	16.5	9.8	20.0	330	6
7-May	16.2	10.5	26.1	20	6
8-May	16.7	10.1	1.7	10	11
9-May	17.0	9.3	1.3	50	6
10-May	16.0	9.3	1.1	70	12
11-May	16.2	9.6	0.8	120	6
12-May	15.8	7.5	tr	160	10
13-May	14.0	5.4	0.0	160	10
14-May	15.6	6.0	0.6	220	12
15-May	15.7	6.0	tr	160	14
16-May	18.4	5.7	1.2	180	16
17-May	15.7	7.5	0.0	180	8
18-May	14.2	7.7	0.1	150	20
19-May	15.3	5.9	0.6	160	14
20-May	14.1	6.4	tr	150	8

21-May	14.9	5.8	4.3	120	14
22-May	14.6	6.7	6.1	140	12
23-May	14.0	6.3	1.6	90	24
24-May	14.0	-0.5	0.2	180	14
25-May	13.2	5.0	4.9	0	0
26-May	14.4	8.8	tr	250	6
27-May	14.5	6.4	0.3	210	7
28-May	14.1	7.5	tr	130	12
29-May	15.8	5.9	0.0	120	12
30-May	15.0	5.8	1.0	130	6
31-May	16.7	2.1	0.5	180	7
Average	**15.1**	**6.2**	**3.0**		**9.5**
1-Jun	17.4	9.6	0.0	150	14
2-Jun	21.6	10.5	0.0	160	14
3-Jun	23.5	10.4	0.0	90	2
4-Jun	23.6	9.2	0.0	360	7
5-Jun	23.4	8.5	1.4	340	7
6-Jun	17.1	7.8	0.7	130	2
7-Jun	16.7	8.1	1.2	360	10
8-Jun	15.7	7.7	3.7	30	8
9-Jun	15.7	5.9	tr	160	10
10-Jun	15.0	4.8	tr	120	2
11-Jun	13.1	5.2	7.5	60	2
12-Jun	14.9	5.7	4.1	150	2
13-Jun	15.5	9.2	tr	120	4
14-Jun	18.7	6.3	0.2	190	6
15-Jun	15.3	10.2	0.0	20	2
16-Jun	17.1	9.3	0.0	240	2
17-Jun	17.8	5.9	2.4	120	2
18-Jun	14.1	5.5	2.9	60	7
19-Jun	19.6	6.3	5.5	210	2
20-Jun	16.1	10.4	3.5	300	2
21-Jun	12.7	12.0	22.2	30	7
22-Jun	16.2	10.2	0.1	40	7
23-Jun	16.4	9.5	2.3	90	2
24-Jun	16.7	6.5	0.0	220	2
25-Jun	17.8	8.3	1.7	50	2
26-Jun	19.2	12.7	0.7	150	7
27-Jun	15.8	14.1	4.3	150	2
28-Jun	18.2	8.4	0.0	200	5
29-Jun	17.8	6.3	0.0	180	7
30-Jun	18.4	6.6	1.0	200	7
Average	**17.4**	**8.4**	**2.4**		**5.2**
1-July	19.2	9.4	0.0	220	2
2-July	19.0	7.8	0.0	80	2
3-July	22.1	7.7	0.0	130	6
4-July	19.8	7.4	0.0	360	7
5-July	17.6	14.4	29.4	30	8
6-July	15.6	13.6	18.9	30	12

7-July	17.4	9.9	0.6	40	10
8-July	17.7	8.4	0.0	40	10
9-July	19.0	12.1	12.5	0	0
10-July	19.2	11.1	8.6	0	0
11-July	15.4	11.3	1.0	360	5
12-July	15.7	11.5	0.0	0	0
13-July	17.2	6.1	0.0	0	0
14-July	22.1	7.3	0.0	110	4
15-July	20.5	9.8	9.2	140	4
16-July	20.5	13.0	8.0	50	6
17-July	20.5	12.4	0.2	330	9
18-July	19.0	11.1	0.3	230	8
19-July	19.2	11.1	12.5	210	7
20-July	15.7	11.4	tr	350	2
21-July	14.9	10.6	tr	180	2
22-July	16.1	6.8	tr	140	2
23-July	18.4	6.1	0.0	290	6
24-July	20.4	6.5	0.4	110	3
25-July	17.8	10.2	tr	250	6
26-July	18.3	9.8	0.0	70	2
27-July	20.1	12.4	1.3	200	2
28-July	16.3	9.8	2.5	0	0
29-July	18.9	9.4	0.0	90	2
30-July	19.0	12.0	0.0	180	2
31-July	19.4	11.8	0.0	70	2
Average	**18.5**	**10.1**	**3.9**		**4.2**
1-Aug	19.7	11.7	18.0	110	2
2-Aug	18.2	13.9	3.5	30	2
3-Aug	20.7	14.1	0.4	90	2
4-Aug	18.2	13.2	7.4	30	8
5-Aug	18.0	13.4	0.0	210	12
6-Aug	19.7	13.2	33.2	90	2
7-Aug	16.9	12.1	3.3	220	2
8-Aug	18.7	10.3	tr	230	15
9-Aug	18.7	9.8	7.6	330	10
10-Aug	13.9	9.7	36.1	120	7
11-Aug	14.6	10.6	0.5	40	8
12-Aug	16.0	11.2	2.5	40	8
13-Aug	19.0	13.8	0.0	140	9
14-Aug	19.6	11.4	tr	225	8
15-Aug	18.9	8.0	0.0	225	7
16-Aug	15.6	9.2	3.8	90	2
17-Aug	19.2	6.6	0.1	280	8
18-Aug	16.2	11.4	3.9	180	2
19-Aug	16.9	8.0	1.2	240	2
20-Aug	18.1	7.1	0.0	230	12
21-Aug	20.6	9.1	0.2	260	6
22-Aug	17.3	8.2	tr	280	6
23-Aug	17.0	11.3	0.0	130	6
24-Aug	17.6	9.4	tr	130	2
25-Aug	17.1	7.2	0.0	140	2
26-Aug	17.4	9.4	3.8	90	5

27-Aug	17.5	11.0	0.0	100	2
28-Aug	17.6	9.0	tr	300	12
29-Aug	15.1	8.8	0.2	310	10
30-Aug	18.4	11.0	0.0	280	2
31-Aug	15.2	7.0	0.0	0	0
Average	**17.7**	**10.3**	**4.8**		**5.8**
1-Sep	15.7	10.7	2.2	170	2
2-Sep	15.4	12.2	2.5	250	10
3-Sep	18.0	11.8	1.3	60	2
4-Sep	18.4	6.9	8.9	210	2
5-Sep	18.5	10.4	3.5	240	2
6-Sep	16.4	11.2	0.8	240	14
7-Sep	17.6	9.3	0.1	270	10
8-Sep	18.1	8.1	0.8	240	8
9-Sep	18.0	9.9	6.0	110	2
10-Sep	18.9	8.3	1.3	110	6
11-Sep	16.0	7.8	6.8	210	15
12-Sep	16.7	11.8	0.6	230	20
13-Sep	15.4	12.1	0.6	270	24
14-Sep	15.8	10.0	0.0	270	12
15-Sep	14.8	8.3	0.0	270	2
16-Sep	12.5	10.1	12.1	130	12
17-Sep	16.6	10.1	2.6	220	2
18-Sep	16.8	10.1	3.3	10	8
19-Sep	16.4	7.1	tr	200	2
20-Sep	15.7	8.7	tr	220	11
21-Sep	15.4	9.0	tr	220	18
22-Sep	14.4	7.8	1.4	260	15
23-Sep	16.2	9.9	0.0	230	10
24-Sep	17.4	12.6	0.0	220	9
25-Sep	17.4	8.5	1.4	150	2
26-Sep	15.7	8.4	0.2	250	15
27-Sep	17.6	7.9	0.0	20	2
28-Sep	23.0	12.4	0.0	130	2
29-Sep	21.0	12.7	0.0	120	2
30-Sep	23.3	12.6	0.7	150	2
Average	**17.1**	**9.9**	**2.1**		**8.1**
1-Oct	16.2	14.9	8.4	120	2
2-Oct	16.2	12.6	2.1	80	2
3-Oct	17.7	10.1	tr	250	12
4-Oct	16.1	9.4	tr	250	14
5-Oct	17.7	10.6	0.5	240	20
6-Oct	11.8	5.0	0.3	250	16
7-Oct	11.7	6.0	tr	300	10
8-Oct	14.5	7.1	3.3	240	3
9-Oct	17.8	8.3	0.7	240	9
10-Oct	14.4	9.7	tr	270	3
11-Oct	13.3	7.1	1.2	270	7
12-Oct	12.2	5.8	tr	70	2

13-Oct	14.1	8.3	0.0	150	2
14-Oct	13.7	10.6	0.3	120	2
15-Oct	12.8	7.5	0.4	250	2
16-Oct	14.4	7.1	1.7	240	2
17-Oct	7.8	7.2	21.6	270	12
18-Oct	10.9	3.2	tr	320	16
19-Oct	8.6	1.7	0.2	20	4
20-Oct	11.8	0.9	3.2	320	2
21-Oct	13.0	5.6	0.0	320	18
22-Oct	12.8	5.5	1.1	270	10
23-Oct	14.8	5.5	0.2	0	0
24-Oct	13.0	5.9	6.0	240	16
25-Oct	12.3	11.1	5.6	240	16
26-Oct	12.6	8.4	0.8	0	0
27-Oct	12.8	7.5	tr	0	0
28-Oct	12.0	4.6	12.5	330	2
29-Oct	14.0	7.7	0.7	280	10
30-Oct	14.5	7.5	4.2	120	4
31-Oct	15.7	7.6	0.5	0	0
Average	**13.6**	**7.4**	**3.1**		**7.0**
1-Nov	12.3	9.3	tr	150	8
2-Nov	13.1	4.3	6.8	150	8
3-Nov	15.1	9.5	0.2	100	7
4-Nov	12.6	9.3	0.1	0	0
5-Nov	12.5	1.0	0.0	0	0
6-Nov	12.6	-0.1	tr	0	0
7-Nov	9.8	-0.3	0.3	280	2
8-Nov	10.8	1.4	0.8	120	7
9-Nov	12.1	9.7	1.0	150	7
10-Nov	13.3	10.2	0.1	140	2
11-Nov	12.7	8.9	6.8	120	10
12-Nov	11.9	7.8	tr	210	10
13-Nov	11.5	8.1	0.3	120	8
14-Nov	10.2	9.1	0.8	130	7
15-Nov	10.0	9.3	tr	120	8
16-Nov	10.5	9.0	1.3	120	2
17-Nov	13.4	6.4	1.9	80	2
18-Nov	13.9	8.1	0.0	230	12
19-Nov	11.3	7.9	0.9	60	2
20-Nov	11.7	6.4	0.3	150	2
21-Nov	11.4	7.4	8.6	120	2
22-Nov	11.2	7.2	tr	270	2
23-Nov	12.6	4.3	1.7	230	28
24-Nov	12.3	7.2	2.1	130	2
25-Nov	11.7	3.1	2.0	240	16
26-Nov	13.6	4.1	4.1	240	20
27-Nov	9.2	2.1	0.4	250	24
28-Nov	12.8	3.8	9.1	240	8
29-Nov	13.8	5.3	3.3	180	20
30-Nov	10.1	1.6	5.0	230	12

Average	**12.0**	**6.0**	**2.3**		**7.9**
1-Dec	10.2	2.2	tr	270	2
2-Dec	9.6	-1.6	0.0	270	2
3-Dec	9.4	1.1	0.0	260	3
4-Dec	9.4	0.0	0.0	0	0
5-Dec	2.7	-1.7	0.0	0	0
6-Dec	4.0	-2.5	7.5	0	0
7-Dec	7.7	-2.0	0.2	270	12
8-Dec	10.2	0.8	2.2	200	16
9-Dec	9.8	1.7	0.0	0	0
10-Dec	9.1	1.0	tr	0	0
11-Dec	6.9	1.2	0.2	270	2
12-Dec	6.2	1.2	1.5	270	8
13-Dec	4.6	1.4	10.1	270	22
14-Dec	5.6	2.9	0.3	260	8
15-Dec	4.2	-0.2	2.0	360	2
16-Dec	3.8	-2.1	0.0	40	7
17-Dec	3.8	-1.2	0.0	280	2
18-Dec	3.7	-2.0	0.3	270	2
19-Dec	5.4	-2.0	5.3	0	0
20-Dec	4.9	0.4	3.5	270	2
21-Dec	11.2	1.6	0.4	0	0
22-Dec	11.9	2.4	0.2	250	10
23-Dec	8.7	4.1	tr	270	2
24-Dec	11.2	0.4	0.7	230	14
25-Dec	12.9	5.3	1.7	240	24
26-Dec	12.3	4.8	0.0	240	26
27-Dec	10.1	3.7	1.3	0	0
28-Dec	10.8	4.3	0.9	230	30
29-Dec	5.2	-0.1	0.9	230	4
30-Dec	7.0	0.8	9.8	280	2
31-Dec	10.9	0.5	5.3	240	2
Average	**7.9**	**0.9**	**1.9**		**6.6**
			2012		
1-Jan	7.2	0.2	1.4	240	10
2-Jan	9.0	1.1	11.2	240	10
3-Jan	9.1	-2.6	0.3	240	48
4-Jan	8.2	-4.1	7.1	270	12
5-Jan	5.9	3.1	0.1	20	16
6-Jan	5.7	0.8	0.0	260	2
7-Jan	5.3	1.1	0.0	300	12
8-Jan	9.6	2.1	tr	240	2
9-Jan	9.4	3.0	0.0	270	3
10-Jan	8.9	3.2	0.0	240	14
11-Jan	10.7	3.1	0.8	0	0
12-Jan	7.9	3.1	0.1	310	9
13-Jan	5.4	-0.8	0.0	0	0
14-Jan	5.5	-3.1	0.0	0	0
15-Jan	5.5	-3.1	0.0	0	0
16-Jan	1.8	-5.0	0.0	0	0
17-Jan	10.0	-4.2	0.2	0	0

18-Jan	8.6	0.7	tr	270	14
19-Jan	4.7	1.4	0.7	280	7
20-Jan	9.5	0.1	0.2	290	8
21-Jan	7.4	1.9	0.0	300	12
22-Jan	7.5	3.2	0.0	340	11
23-Jan	6.7	0.5	2.4	280	6
24-Jan	9.3	0.1	1.6	0	0
25-Jan	10.2	1.8	2.8	180	12
26-Jan	4.6	-0.9	3.2	0	0
27-Jan	5.5	-1.1	0.0	0	0
28-Jan	5.4	-2.5	0.0	0	0
29-Jan	5.5	-2.5	0.4	0	0
30-Jan	4.3	-2.5	0.3	120	2
31-Jan	4.6	1.6	0.0	120	10
Average	**7.1**	**0.0**	**1.1**		**7.1**
1-Feb	4.1	2.9	0.0	150	2
2-Feb	2.3	-3.2	0.0	0	0
3-Feb	n/a	-5.3	0.0	300	2
4-Feb	4.0	n/a	0.0	210	6
5-Feb	5.3	-3.6	10.2	0	0
6-Feb	6.9	-3.7	0.2	0	0
7-Feb	3.4	-3.8	0.0	0	0
8-Feb	3.2	-1.5	5.4	230	2
9-Feb	6.2	0.0	1.0	270	2
10-Feb	3.8	2.5	0.0	120	2
11-Feb	8.4	2.0	2.2	220	3
12-Feb	8.1	2.1	0.1	0	0
13-Feb	9.8	0.4	0.0	210	2
14-Feb	10.7	3.8	0.0	210	12
15-Feb	12.7	5.6	tr	330	14
16-Feb	8.8	4.9	0.0	270	12
17-Feb	5.9	2.8	0.0	240	2
18-Feb	5.0	0.8	0.6	240	6
19-Feb	6.0	-1.0	0.3	250	2
20-Feb	10.7	-0.4	tr	240	14
21-Feb	12.3	5.7	0.4	240	7
22-Feb	13.9	9.7	0.1	240	14
23-Feb	14.4	8.7	0.0	250	22
24-Feb	10.5	6.6	0.0	290	14
25-Feb	11.1	3.2	0.0	220	3
26-Feb	11.1	3.0	0.3	0	0
27-Feb	13.2	3.0	0.7	270	7
28-Feb	14.7	9.6	tr	260	14
29-Feb	11.8	7.2	0.0	260	2
Average	**8.5**	**2.2**	**0.8**		**5.7**
1-Mar	13.4	8.1	1.8	230	7
2-Mar	12.9	6.1	0.0	0	0
3-Mar	13.1	3.0	0.3	120	8

4-Mar	10.7	5.9	0.3	240	2
5-Mar	9.5	-1.5	0.0	240	2
6-Mar	11.5	-1.7	0.7	0	0
7-Mar	9.3	1.6	0.0	270	10
8-Mar	12.3	0.2	0.0	250	7
9-Mar	13.0	4.9	0.0	260	26
10-Mar	13.0	4.1	0.0	240	13
11-Mar	16.4	4.7	tr	250	10
12-Mar	13.7	3.2	0.0	250	6
13-Mar	11.9	6.4	0.0	270	7
14-Mar	10.6	6.4	0.0	270	7
15-Mar	10.6	3.6	0.2	240	7
16-Mar	12.0	6.4	0.5	240	12
17-Mar	12.4	2.5	0.0	270	8
18-Mar	12.4	-0.1	0.0	0	0
19-Mar	11.3	-0.4	0.0	270	6
20-Mar	14.3	7.0	0.0	270	14
21-Mar	15.2	6.5	0.0	270	10
22-Mar	12.4	1.0	0.0	230	2
23-Mar	10.5	4.6	0.0	110	7
24-Mar	12.6	6.5	0.0	0	0
25-Mar	19.7	2.0	0.0	0	0
26-Mar	20.3	2.2	0.0	0	0
27-Mar	21.6	2.8	tr	250	2
28-Mar	20.6	4.2	0.0	210	4
29-Mar	20.6	9.8	0.0	280	10
30-Mar	18.2	7.6	0.0	320	12
31-Mar	18.4	6.0	1.3	260	3
Average	**14.0**	**4.0**	**0.2**		**6.5**
1-Apr	14.8	-0.6	0.8	240	2
2-Apr	6.1	4.6	27.2	30	4
3-Apr	5.2	0.9	1.1	30	20
4-Apr	6.8	0.7	0.0	60	14
5-Apr	11.1	-3.2	tr	260	6
6-Apr	9.7	4.6	0.8	270	2
7-Apr	10.1	5.1	0.0	260	2
8-Apr	14.2	5.2	0.1	240	2
9-Apr	10.9	4.9	5.1	230	14
10-Apr	11.1	4.6	5.7	300	4
11-Apr	12.8	2.8	3.7	280	2
12-Apr	10.4	4.7	0.1	340	6
13-Apr	9.5	2.2	0.0	350	4
14-Apr	9.8	1.6	0.0	0	0
15-Apr	9.8	-0.9	0.6	0	0
16-Apr	9.3	-0.5	9.7	0	0
17-Apr	11.0	3.9	2.7	360	5
18-Apr	10.1	3.0	tr	360	7
19-Apr	9.2	4.9	10.2	30	10
20-Apr	11.5	5.7	2.2	30	2
21-Apr	11.4	5.9	2.2	330	6
22-Apr	11.3	5.6	5.0	0	0
23-Apr	10.4	4.7	4.1	350	6

24-Apr	9.7	5.2	4.5	30	10
25-Apr	9.0	5.6	5.3	70	12
26-Apr	10.8	6.5	0.7	40	16
27-Apr	10.9	0.4	0.0	330	10
28-Apr	10.5	0.3	0.0	0	0
29-Apr	10.8	-1.0	10.3	280	5
30-Apr	11.7	-0.8	tr	50	14
Average	**10.3**	**2.9**	**3.8**		**6.2**
1-May	13.8	5.8	0.1	30	8
2-May	10.9	5.1	0.0	160	8
3-May	13.0	6.1	0.1	270	3
4-May	13.3	6.2	0.3	60	14
5-May	10.9	2.1	6.5	300	3
6-May	8.8	3.1	tr	240	2
7-May	10.6	1.9	5.6	130	8
8-May	13.6	2.9	0.1	270	10
9-May	12.7	2.7	5.1	270	4
10-May	8.2	5.4	9.7	70	14
11-May	9.0	4.5	4.9	320	4
12-May	12.7	4.1	0.0	210	2
13-May	11.0	4.7	1.0	230	15
14-May	13.6	5.5	2.9	270	14
15-May	11.7	3.4	0.0	30	10
16-May	12.8	2.3	5.3	30	10
17-May	6.8	4.1	3.7	30	10
18-May	8.9	3.8	0.0	80	14
19-May	10.9	3.0	0.0	90	11
20-May	12.0	1.0	0.0	0	0
21-May	15.5	1.0	0.4	180	5
22-May	19.9	7.8	0.0	140	4
23-May	21.2	7.8	2.6	150	2
24-May	22.5	10.9	tr	170	2
25-May	21.9	11.4	0.0	160	6
26-May	22.7	10.7	0.0	210	2
27-May	23.1	11.1	0.0	210	2
28-May	20.8	10.2	0.0	140	2
29-May	12.3	9.0	tr	150	2
30-May	11.2	8.2	11.6	120	4
31-May	12.5	9.1	5.2	120	2
Average	**13.8**	**5.6**	**2.3**		**6.4**
1-Jun	15.0	8.4	0.0	0	0
2-Jun	15.2	7.8	0.0	0	0
3-Jun	15.1	5.0	1.2	30	10
4-Jun	15.2	2.9	tr	0	0
5-Jun	15.0	5.6	1.9	0	0
6-Jun	12.3	10.5	9.1	n/a	10
7-Jun	14.9	8.2	19.0	0	0
8-Jun	11.9	10.6	0.2	0	0
9-Jun	11.1	9.7	2.1	n/a	2

10-Jun	13.3	9.3	tr	n/a	2
11-Jun	12.0	8.7	0.0	0	0
12-Jun	13.6	3.7	3.2	0	0
13-Jun	14.0	6.1	0.5	0	0
14-Jun	13.2	7.8	0.8	n/a	12
15-Jun	10.2	8.4	4.8	n/a	18
16-Jun	10.1	8.2	7.5	n/a	14
17-Jun	12.0	8.1	9.3	n/a	2
18-Jun	15.7	8.7	tr	0	0
19-Jun	18.3	6.8	0.0	180	2
20-Jun	15.8	5.7	0.0	120	7
21-Jun	15.3	9.9	47.7	90	14
22-Jun	15.1	11.5	0.0	100	8
23-Jun	15.9	9.9	0.0	270	9
24-Jun	18.7	8.9	0.2	270	2
25-Jun	18.7	10.2	0.0	340	4
26-Jun	17.4	11.0	14.4	130	8
27-Jun	15.2	11.7	5.2	90	2
28-Jun	15.3	12.2	0.2	120	10
29-Jun	17.5	11.3	11.2	210	2
30-Jun	17.6	10.5	2.6	240	8
Average	**14.7**	**8.6**	**5.2**		**4.9**
1-July	18.3	10.5	4.5	260	2
2-July	15.8	10.2	3.7	100	9
3-July	18.9	11.6	tr	0	0
4-July	19.6	12.9	tr	130	4
5-July	20.0	13.9	tr	150	8
6-July	18.2	14.5	0.2	30	16
7-July	16.1	12.1	12.7	310	10
8-July	16.3	11.6	1.0	240	2
9-July	15.5	12.5	tr	180	2
10-July	13.5	10.8	6.3	180	2
11-July	14.0	9.7	7.1	90	3
12-July	17.1	9.8	tr	280	2
13-July	13.5	10.0	0.0	100	2
14-July	16.2	9.2	0.0	0	0
15-July	16.3	7.1	1.5	270	10
16-July	19.8	7.2	0.0	270	7
17-July	17.5	8.7	17.7	300	10
18-July	14.0	12.0	13.8	30	9
19-July	15.6	7.8	2.3	310	9
20-July	14.9	8.9	0.0	230	6
21-July	16.9	7.9	0.0	300	2
22-July	19.0	8.7	0.8	240	7
23-July	17.5	14.5	4.6	270	10
24-July	20.7	12.1	tr	270	4
25-July	19.6	10.8	0.0	300	2
26-July	17.8	10.6	tr	130	8
27-July	18.5	9.3	0.0	260	14
28-July	18.1	9.1	4.2	270	6
29-July	18.6	9.8	15.3	220	4
30-July	15.4	8.3	1.1	270	2

31-July	18.2	6.8	4.5	260	2
Average	**17.1**	**10.3**	**4.2**		**5.6**
1-Aug	18.8	12.7	1.3	120	6
2-Aug	20.5	11.2	0.0	250	6
3-Aug	20.3	8.4	0.0	200	2
4-Aug	20.1	11.8	0.0	240	2
5-Aug	20.1	10.9	39.8	0	2
6-Aug	18.2	13.1	2.2	240	2
7-Aug	20.4	12.2	tr	200	2
8-Aug	18.1	12.6	tr	120	4
9-Aug	20.0	10.8	0.0	230	2
10-Aug	20.5	13.2	0.0	180	4
11-Aug	21.1	10.5	0.0	0	0
12-Aug	20.8	10.0	4.3	110	4
13-Aug	17.4	10.3	2.3	120	10
14-Aug	21.2	14.5	0.0	90	2
15-Aug	18.9	12.6	11.8	90	8
16-Aug	20.9	13.2	7.2	160	4
17-Aug	19.9	8.3	6.1	120	10
18-Aug	22.7	17.1	0.0	300	2
19-Aug	20.7	18.7	11.7	0	0
20-Aug	21.3	10.7	0.8	0	0
21-Aug	n/a	11.1	12.5	0	0
22-Aug	20.8	10.8	0.1	270	10
23-Aug	n/a	10.6	tr	260	10
24-Aug	18.8	12.2	0.0	260	2
25-Aug	19.5	10.5	0.0	0	0
26-Aug	19.3	7.0	2.1	0	0
27-Aug	15.0	7.2	13.3	110	8
28-Aug	18.1	7.0	4.6	240	18
29-Aug	0.0	10.6	5.5	120	2
30-Aug	15.7	7.4	0.0	30	12
31-Aug	14.7	3.3	0.3	280	2
Average	**18.8**	**11.0**	**4.5**		**4.4**
1-Sep	12.1	2.9	0.0	240	11
2-Sep	21.2	5.3	0.0	300	2
3-Sep	20.7	13.3	0.0	270	12
4-Sep	19.5	11.8	0.0	270	16
5-Sep	18.8	8.7	0.0	270	10
6-Sep	17.0	7.3	0.5	240	16
7-Sep	22.5	13.3	0.0	250	2
8-Sep	21.0	12.6	0.0	260	5
9-Sep	22.3	8.5	2.0	0	0
10-Sep	16.2	8.4	2.1	270	2
11-Sep	14.8	1.2	0.0	260	12
12-Sep	15.2	5.2	0.0	270	7
13-Sep	16.0	5.4	tr	240	10
14-Sep	15.9	10.5	0.0	280	16
15-Sep	18.7	9.7	0.0	240	9

16-Sep	15.5	9.5	1.6	240	15
17-Sep	15.6	6.8	3.4	240	10
18-Sep	14.0	4.8	0.0	260	7
19-Sep	15.3	2.3	1.0	270	4
20-Sep	11.2	5.7	5.5	0	0
21-Sep	13.6	2.3	1.4	0	0
22-Sep	14.5	1.1	0.0	0	0
23-Sep	14.0	1.0	tr	0	0
24-Sep	12.5	0.8	5.9	n/a	20
25-Sep	13.0	7.2	17.2	40	46
26-Sep	15.3	9.4	0.1	30	16
27-Sep	13.9	6.4	tr	340	2
28-Sep	12.9	8.1	0.0	240	10
29-Sep	12.0	6.5	0.3	210	3
30-Sep	16.8	6.9	0.6	210	7
Average	**16.1**	**6.8**	**1.5**		**9.0**
1-Oct	14.8	9.9	4.2	240	10
2-Oct	13.8	6.5	3.4	230	12
3-Oct	13.0	6.0	1.2	270	7
4-Oct	12.5	1.5	2.2	0	0
5-Oct	14.8	4.8	0.0	0	0
6-Oct	14.0	2.5	0.0	0	0
7-Oct	13.9	1.5	0.1	0	0
8-Oct	13.5	0.1	0.0	0	0
9-Oct	11.4	-1.2	0.0	280	2
10-Oct	12.3	-0.7	1.7	0	0
11-Oct	12.4	3.3	51.5	0	0
12-Oct	12.4	10.0	0.9	90	10
13-Oct	9.1	8.1	8.4	240	2
14-Oct	9.8	7.3	1.7	0	0
15-Oct	10.5	1.2	4.8	280	2
16-Oct	8.8	2.0	0.7	30	8
17-Oct	8.9	-1.0	15.2	30	8
18-Oct	12.8	5.2	1.2	30	2
19-Oct	10.5	7.2	0.0	60	10
20-Oct	14.7	7.9	0.0	0	0
21-Oct	13.8	3.8	1.9	0	0
22-Oct	11.7	2.8	0.4	260	2
23-Oct	11.8	6.8	0.0	60	2
24-Oct	12.5	5.6	0.0	180	2
25-Oct	11.8	6.1	0.0	0	0
26-Oct	11.2	0.5	0.0	310	2
27-Oct	10.1	-0.7	0.0	240	2
28-Oct	10.4	4.0	0.2	240	2
29-Oct	9.4	1.2	0.1	330	2
30-Oct	9.6	1.2	0.4	240	2
31-Oct	7.2	5.7	7.1	250	2
Average	**11.7**	**3.8**	**3.5**		**2.9**
1-Nov	7.2	-1.2	4.1	0	0

2-Nov	6.9	0.2	0.0	230	20
3-Nov	6.1	-1.9	0.0	0	0
4-Nov	9.3	-2.0	3.8	0	0
5-Nov	9.2	-0.6	0.4	250	2
6-Nov	12.4	0.7	0.0	250	12
7-Nov	12.4	6.8	0.0	270	7
8-Nov	12.0	7.0	0.2	270	5
9-Nov	12.3	6.0	0.0	270	10
10-Nov	9.0	7.1	0.0	240	2
11-Nov	8.0	2.7	1.8	240	2
12-Nov	12.5	-1.2	1.5	0	0
13-Nov	13.9	3.0	1.7	210	15
14-Nov	9.8	7.3	0.2	0	0
15-Nov	9.3	1.8	0.8	0	0
16-Nov	9.1	4.7	0.0	270	7
17-Nov	8.8	3.2	0.0	0	0
18-Nov	9.6	1.5	7.1	0	0
19-Nov	11.8	1.2	tr	210	18
20-Nov	12.8	8.7	0.8	150	2
21-Nov	10.1	4.5	1.6	0	0
22-Nov	8.5	1.6	15.4	160	12
23-Nov	7.9	3.4	0.0	270	11
24-Nov	6.0	1.7	3.6	120	2
25-Nov	5.8	5.1	1.4	0	0
26-Nov	6.9	-0.2	tr	20	8
27-Nov	7.8	4.1	0.0	350	6
28-Nov	6.0	-1.0	0.0	270	2
29-Nov	3.5	-1.7	0.0	0	0
30-Nov	4.4	-2.4	0.9	270	2
Average	**9.0**	**2.3**	**1.6**		**4.8**

1-Dec	4.5	-1.8	0.0	280	2
2-Dec	4.7	-2.2	1.5	0	0
3-Dec	3.3	-2.3	tr	0	0
4-Dec	2.8	0.3	2.3	0	0
5-Dec	2.8	-1.2	0.0	360	12
6-Dec	3.0	-4.5	5.2	360	14
7-Dec	3.9	0.2	0.0	0	0
8-Dec	4.9	-1.1	0.0	0	0
9-Dec	6.9	0.3	0.7	40	9
10-Dec	5.2	1.2	tr	30	12
11-Dec	1.3	-2.9	0.0	0	0
12-Dec	2.6	-3.7	0.0	0	0
13-Dec	3.2	-5.7	tr	0	0
14-Dec	6.7	-3.0	24.2	130	12
15-Dec	7.0	2.0	0.0	140	10
16-Dec	7.2	1.9	2.7	0	0
17-Dec	6.5	1.7	0.5	30	12
18-Dec	8.2	3.3	0.2	0	0
19-Dec	7.3	2.8	9.8	130	12
20-Dec	5.9	5.3	50.9	110	26
21-Dec	6.5	4.8	7.7	120	18
22-Dec	6.7	4.8	21.2	120	26

23-Dec	6.2	4.7	0.9	240	2
24-Dec	6.8	4.8	0.3	150	2
25-Dec	7.0	2.1	tr	300	2
26-Dec	5.3	-0.2	4.4	60	2
27-Dec	4.8	1.7	1.9	50	14
28-Dec	12.0	0.3	2.5	110	2
29-Dec	12.2	4.7	2.7	200	21
30-Dec	12.0	1.5	2.6	230	9
31-Dec	13.4	1.0	0.0	220	14
Average	**6.2**	**0.7**	**5.3**		**7.5**
			2013		
1-Jan	7.0	0.7	6.6	220	7
2-Jan	10.8	2.6	0.0	0	0
3-Jan	11.2	2.3	0.4	270	14
4-Jan	10.9	8.8	0.0	270	16
5-Jan	9.8	3.4	0.0	210	12
6-Jan	8.7	2.1	2.7	330	2
7-Jan	8.8	3.7	9.7	0	0
8-Jan	11.2	6.5	0.1	230	2
9-Jan	7.6	1.8	0.0	250	2
10-Jan	5.5	-0.3	0.5	0	0
11-Jan	4.5	0.8	0.0	0	0
12-Jan	4.0	0.5	0.0	0	0
13-Jan	4.5	0.5	6.5	0	0
14-Jan	2.7	0.4	tr	0	0
15-Jan	3.7	-0.8	0.0	0	0
16-Jan	1.6	-3.8	0.1	0	0
17-Jan	2.7	-3.8	0.0	0	0
18-Jan	4.0	0.6	0.3	120	10
19-Jan	2.1	-0.9	0.0	30	7
20-Jan	3.0	0.0	5.7	120	5
21-Jan	2.7	0.8	18.2	100	28
22-Jan	2.7	0.7	6.0	100	18
23-Jan	2.4	-0.2	4.0	0	0
24-Jan	1.7	-0.2	3.2	0	0
25-Jan	1.7	0.0	6.8	0	0
26-Jan	7.0	0.0	9.1	210	4
27-Jan	6.9	0.5	1.7	0	0
28-Jan	7.8	-0.1	5.5	240	26
29-Jan	10.1	3.3	7.4	260	12
30-Jan	8.0	4.0	3.9	260	12
31-Jan	5.7	3.2	1.5	120	2
Average	**5.8**	**1.2**	**3.3**		**5.8**
1-Feb	4.9	2.8	0.0	280	2
2-Feb	5.1	1.7	0.0	320	2
3-Feb	9.5	2.1	0.0	300	10
4-Feb	5.0	2.1	2.7	270	22
5-Feb	6.4	-0.9	0.0	240	16
6-Feb	4.9	1.4	0.0	330	2

7-Feb	4.8	0.2	0.9	290	10
8-Feb	6.5	0.0	0.0	300	10
9-Feb	6.4	2.1	0.0	0	0
10-Feb	6.7	2.0	12.1	120	4
11-Feb	5.6	2.1	0.2	120	10
12-Feb	3.5	2.8	0.4	120	2
13-Feb	4.8	0.0	16.5	160	6
14-Feb	8.2	-0.1	tr	250	2
15-Feb	7.9	1.8	0.0	210	2
16-Feb	6.2	0.1	0.0	210	2
17-Feb	7.9	1.1	0.0	240	2
18-Feb	8.2	-0.3	tr	330	2
19-Feb	7.0	-2.6	1.0	0	0
20-Feb	4.8	-0.5	0.0	140	8
21-Feb	3.6	1.9	0.0	0	0
22-Feb	2.8	0.8	0.0	0	0
23-Feb	4.5	-0.8	0.0	0	0
24-Feb	6.7	-0.5	0.0	0	0
25-Feb	7.8	-1.2	tr	0	0
26-Feb	7.8	-2.5	0.0	270	2
27-Feb	9.7	-4.6	tr	270	2
28-Feb	9.7	-2.2	0.1	0	0
29-Feb					
Average	**6.3**	**0.3**	**1.4**		**4.2**
1-Mar	10.0	0.0	0.0	0	0
2-Mar	12.1	-0.3	0.0	0	0
3-Mar	8.8	-0.9	tr	330	2
4-Mar	6.9	4.1	0.0	0	0
5-Mar	7.7	-1.2	0.0	0	0
6-Mar	5.8	1.4	2.4	90	7
7-Mar	6.4	4.4	5.6	90	14
8-Mar	5.7	3.3	10.3	90	14
9-Mar	4.1	2.9	0.3	60	12
10-Mar	2.6	-0.3	6.4	30	9
11-Mar	1.7	-4.2	tr	20	12
12-Mar	5.0	-5.0	tr	200	2
13-Mar	5.6	-1.3	0.0	0	0
14-Mar	6.2	-1.4	2.1	0	0
15-Mar	5.0	1.2	tr	180	7
16-Mar	5.3	-0.7	1.3	240	2
17-Mar	5.4	0.7	11.2	60	12
18-Mar	3.4	1.3	11.5	90	14
19-Mar	2.4	-0.2	5.7	60	20
20-Mar	4.5	0.2	4.6	120	14
21-Mar	4.3	-1.5	1.2	90	2
22-Mar	2.5	0.8	0.0	120	33
23-Mar	2.5	1.0	0.0	140	22
24-Mar	2.5	0.9	2.3	125	18
25-Mar	3.2	0.4	0.6	100	22
26-Mar	4.5	0.6	tr	120	12
27-Mar	4.5	-0.7	1.3	30	2
28-Mar	6.1	-0.5	0.2	60	7

29-Mar	3.9	-1.4	0.0	0	0
30-Mar	3.7	-1.5	0.0	330	2
31-Mar	5.5	-4.1	tr	0	0
Average	**5.1**	**-0.1**	**2.7**		**8.4**
1-Apr	4.9	-1.5	0.0	140	7
2-Apr	7.0	-1.3	tr	240	2
3-Apr	8.0	-3.2	tr	0	0
4-Apr	8.7	1.2	tr	90	7
5-Apr	7.0	1.6	0.0	10	10
6-Apr	9.9	-3.1	0.0	0	0
7-Apr	9.8	-3.4	2.3	0	0
8-Apr	6.4	-3.3	0.3	120	12
9-Apr	7.0	1.2	0.0	100	18
10-Apr	6.1	1.2	1.3	110	8
11-Apr	6.7	3.5	0.9	110	8
12-Apr	6.3	2.7	0.0	30	5
13-Apr	9.9	2.2	4.5	330	2
14-Apr	13.9	3.1	0.9	210	18
15-Apr	14.5	8.7	5.5	240	22
16-Apr	12.4	8.3	2.9	230	26
17-Apr	11.7	4.3	9.1	120	14
18-Apr	12.9	5.2	0.2	250	32
19-Apr	13.9	1.6	0.0	320	2
20-Apr	14.0	2.5	0.0	220	12
21-Apr	13.9	2.4	0.0	190	12
22-Apr	13.8	2.2	0.0	230	22
23-Apr	14.3	6.8	4.7	250	20
24-Apr	12.3	6.8	0.0	0	0
25-Apr	12.7	5.0	0.0	360	8
26-Apr	11.7	2.0	3.1	270	10
27-Apr	11.1	1.9	0.0	330	7
28-Apr	13.1	3.0	0.4	240	12
29-Apr	13.3	2.9	0.0	300	24
30-Apr	14.3	2.1	tr	280	12
Average	**10.7**	**2.2**	**1.4**		**11.1**
1-May	15.7	5.6	0.2	210	12
2-May	12.5	5.5	tr	180	6
3-May	9.9	8.2	34.2	250	16
4-May	5.5	3.5	0.0	270	12
5-May	3.8	2.6	0.2	270	18
6-May	13.8	2.5	0.0	230	14
7-May	17.7	6.2	0.0	200	2
8-May	12.7	8.7	1.4	90	12
9-May	13.7	6.8	2.4	180	8
10-May	12.6	7.1	1.7	270	6
11-May	13.6	6.5	0.0	210	7
12-May	13.8	5.5	0.9	210	10
13-May	11.8	2.8	0.4	260	24
14-May	12.2	4.5	1.4	220	28

Appendix 3. Temperature and relative humidity monitoring data using iButton DS1923 hygrochron data loggers

Date	Time	First floor wall internal temperature, °C	50 cm wall internal temperature, °C	First floor wall internal relative humidity, %	50 cm wall internal relative humidity, %
01/03/2012	01:00:00	11.057	10.072	82.978	84.808
01/03/2012	13:00:00	10.556	10.072	84.015	85.325
02/03/2012	01:00:00	11.057	10.072	85.045	84.289
02/03/2012	13:00:00	10.054	9.57	84.531	85.84
03/03/2012	01:00:00	9.552	9.069	84.531	86.354
03/03/2012	13:00:00	8.549	8.568	85.045	86.354
04/03/2012	01:00:00	8.047	8.067	84.531	86.354
04/03/2012	13:00:00	6.541	7.565	85.045	86.867
05/03/2012	01:00:00	6.039	7.064	85.045	86.867
05/03/2012	13:00:00	4.533	5.559	86.07	87.378
06/03/2012	01:00:00	5.537	5.559	85.559	87.378
06/03/2012	13:00:00	4.031	4.556	86.58	87.888
07/03/2012	01:00:00	6.541	5.559	85.559	87.378
07/03/2012	13:00:00	8.047	6.061	85.559	87.378
08/03/2012	01:00:00	7.043	6.061	85.559	87.378
08/03/2012	13:00:00	6.039	5.559	86.58	87.378
09/03/2012	01:00:00	8.549	6.562	85.559	87.378
09/03/2012	13:00:00	10.556	7.565	85.559	86.867
10/03/2012	01:00:00	10.556	8.568	85.045	87.888
10/03/2012	13:00:00	9.552	8.568	85.559	87.378
11/03/2012	01:00:00	10.054	8.568	85.559	86.867
11/03/2012	13:00:00	10.054	9.069	86.07	86.867
12/03/2012	01:00:00	11.559	9.57	85.559	86.867
12/03/2012	13:00:00	10.054	8.568	85.559	86.867
13/03/2012	01:00:00	11.559	9.069	85.559	86.354
13/03/2012	13:00:00	10.556	9.069	85.559	86.354
14/03/2012	01:00:00	10.556	9.069	85.559	87.378
14/03/2012	13:00:00	9.552	8.568	85.559	87.378
15/03/2012	01:00:00	9.051	8.568	86.07	87.888
15/03/2012	13:00:00	8.047	8.067	86.07	87.378
16/03/2012	01:00:00	8.549	8.568	86.07	87.888
16/03/2012	13:00:00	9.552	8.568	85.559	87.378
17/03/2012	01:00:00	9.552	9.069	85.559	87.888
17/03/2012	13:00:00	8.047	8.067	86.07	87.888
18/03/2012	01:00:00	8.549	8.067	86.07	87.378
18/03/2012	13:00:00	7.043	7.064	86.58	87.378
19/03/2012	01:00:00	8.047	7.064	86.07	87.888
19/03/2012	13:00:00	7.545	7.064	86.07	87.888

20/03/2012	01:00:00	9.552	8.067	86.58	86.867
20/03/2012	13:00:00	10.556	8.568	86.07	87.378
21/03/2012	01:00:00	11.559	9.57	85.559	88.396
21/03/2012	13:00:00	11.057	9.57	85.559	87.888
22/03/2012	01:00:00	11.559	9.57	85.045	87.378
22/03/2012	13:00:00	9.552	8.568	86.58	88.396
23/03/2012	01:00:00	11.057	8.568	85.559	87.378
23/03/2012	13:00:00	10.054	8.568	86.07	87.378
24/03/2012	01:00:00	10.054	8.568	85.559	87.378
24/03/2012	13:00:00	9.552	8.568	85.559	88.903
25/03/2012	01:00:00	10.556	8.568	86.07	87.378
25/03/2012	13:00:00	9.552	8.067	86.07	87.888
26/03/2012	01:00:00	13.063	9.069	85.559	87.888
26/03/2012	13:00:00	12.06	9.069	85.559	87.378
27/03/2012	01:00:00	14.566	10.072	85.045	87.888
27/03/2012	13:00:00	12.561	9.069	86.07	87.378
28/03/2012	01:00:00	15.067	10.573	84.531	86.354
28/03/2012	13:00:00	14.065	10.072	85.045	88.396
29/03/2012	01:00:00	15.568	11.074	85.045	87.378
29/03/2012	13:00:00	14.566	11.074	84.531	87.378
30/03/2012	01:00:00	14.566	12.076	85.045	86.867
30/03/2012	13:00:00	13.063	11.074	85.559	86.867
31/03/2012	01:00:00	14.065	11.575	85.045	87.378
31/03/2012	13:00:00	12.06	11.074	85.559	87.888
01/04/2012	01:00:00	11.057	10.072	85.559	87.378
01/04/2012	13:00:00	9.552	9.069	86.07	87.888
02/04/2012	01:00:00	11.559	10.072	85.559	87.888
02/04/2012	13:00:00	10.054	9.57	85.559	87.888
03/04/2012	01:00:00	9.051	9.069	86.07	88.396
03/04/2012	13:00:00	6.039	7.565	86.07	88.396
04/04/2012	01:00:00	5.035	6.562	86.58	88.396
04/04/2012	13:00:00	5.035	6.061	86.58	89.408
05/04/2012	01:00:00	5.537	5.559	85.559	88.903
05/04/2012	13:00:00	4.533	4.556	86.58	89.408
06/04/2012	01:00:00	7.043	5.559	86.58	88.903
06/04/2012	13:00:00	8.047	6.061	86.58	88.903
07/04/2012	01:00:00	9.051	7.064	86.07	88.396
07/04/2012	13:00:00	8.047	7.064	86.07	88.903
08/04/2012	01:00:00	10.054	7.565	86.07	88.396
08/04/2012	13:00:00	10.556	8.568	86.07	88.903
09/04/2012	01:00:00	10.054	8.568	85.559	88.396
09/04/2012	13:00:00	9.051	8.568	85.559	87.888
10/04/2012	01:00:00	9.051	8.568	84.531	88.903
10/04/2012	13:00:00	8.549	8.067	85.559	88.396
11/04/2012	01:00:00	8.549	8.067	85.559	88.903
11/04/2012	13:00:00	8.549	8.067	85.559	88.903

12/04/2012	01:00:00	9.051	8.067	86.07	88.396
12/04/2012	13:00:00	8.549	7.565	85.559	88.903
13/04/2012	01:00:00	8.549	7.565	86.07	88.396
13/04/2012	13:00:00	7.545	7.064	86.07	88.396
14/04/2012	01:00:00	7.545	7.064	85.045	88.903
14/04/2012	13:00:00	7.043	6.562	87.089	88.396
15/04/2012	01:00:00	7.043	6.061	86.07	89.912
15/04/2012	13:00:00	6.039	5.559	86.07	88.903
16/04/2012	01:00:00	7.043	5.559	86.07	89.408
16/04/2012	13:00:00	6.541	5.559	86.07	89.408
17/04/2012	01:00:00	8.047	6.061	85.045	88.396
17/04/2012	13:00:00	7.545	6.061	85.045	88.903
18/04/2012	01:00:00	8.047	6.562	85.559	89.408
18/04/2012	13:00:00	8.047	6.562	85.559	88.903
19/04/2012	01:00:00	9.051	7.064	85.559	88.903
19/04/2012	13:00:00	8.549	7.064	85.045	88.903
20/04/2012	01:00:00	9.051	7.064	86.07	90.414
20/04/2012	13:00:00	8.549	7.565	85.559	88.903
21/04/2012	01:00:00	9.051	7.565	86.58	88.903
21/04/2012	13:00:00	9.051	7.565	85.559	88.396
22/04/2012	01:00:00	9.051	8.067	84.531	88.396
22/04/2012	13:00:00	9.051	8.067	85.559	88.396
23/04/2012	01:00:00	9.552	8.067	85.045	88.396
23/04/2012	13:00:00	9.051	7.565	85.559	88.903
24/04/2012	01:00:00	9.051	8.067	85.045	88.903
24/04/2012	13:00:00	8.549	7.565	84.531	88.903
25/04/2012	01:00:00	8.549	7.565	85.045	88.903
25/04/2012	13:00:00	8.047	7.565	85.045	88.903
26/04/2012	01:00:00	8.047	7.565	85.559	88.903
26/04/2012	13:00:00	8.549	7.565	85.045	88.396
27/04/2012	01:00:00	8.549	8.067	85.045	88.396
27/04/2012	13:00:00	7.545	7.064	85.559	88.903
28/04/2012	01:00:00	7.043	7.064	85.045	88.903
28/04/2012	13:00:00	6.541	6.562	86.07	89.408
29/04/2012	01:00:00	7.545	6.562	85.045	89.408
29/04/2012	13:00:00	6.541	6.061	85.559	89.408
30/04/2012	01:00:00	8.047	6.562	84.531	88.903
30/04/2012	13:00:00	7.545	6.562	86.07	89.408
01/05/2012	01:00:00	9.051	7.064	85.045	88.903
01/05/2012	13:00:00	9.552	7.565	85.045	89.912
02/05/2012	01:00:00	10.556	8.067	85.045	88.396
02/05/2012	13:00:00	10.556	8.067	84.531	88.903
03/05/2012	01:00:00	11.559	8.568	84.015	88.903
03/05/2012	13:00:00	10.556	8.568	85.045	88.903
04/05/2012	01:00:00	12.06	9.069	84.015	88.396
04/05/2012	13:00:00	11.057	8.568	84.531	88.903

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05/05/2012	13:00:00	7.545	7.064	85.045	88.903
06/05/2012	01:00:00	9.051	7.064	85.045	88.903
06/05/2012	13:00:00	8.549	7.064	85.045	89.912
07/05/2012	01:00:00	8.047	7.064	85.045	89.408
07/05/2012	13:00:00	7.545	6.562	85.045	89.408
08/05/2012	01:00:00	8.047	7.064	85.559	88.903
08/05/2012	13:00:00	9.051	7.565	85.045	89.408
09/05/2012	01:00:00	10.054	8.067	84.531	88.396
09/05/2012	13:00:00	9.552	7.565	85.045	90.414
10/05/2012	01:00:00	10.556	8.067	84.531	89.408
10/05/2012	13:00:00	9.552	8.067	85.045	88.903
11/05/2012	01:00:00	8.549	8.067	86.07	89.408
11/05/2012	13:00:00	8.047	7.565	84.531	88.903
12/05/2012	01:00:00	8.047	7.565	85.045	88.903
12/05/2012	13:00:00	8.047	7.565	85.045	87.888
13/05/2012	01:00:00	10.556	8.067	84.531	89.408
13/05/2012	13:00:00	10.556	8.568	84.531	89.408
14/05/2012	01:00:00	10.054	8.568	84.531	88.396
14/05/2012	13:00:00	9.552	8.568	84.531	88.903
15/05/2012	01:00:00	10.054	9.069	84.531	89.408
15/05/2012	13:00:00	9.051	8.568	84.531	89.408
16/05/2012	01:00:00	9.051	8.067	85.045	88.396
16/05/2012	13:00:00	8.549	7.565	85.045	88.903
17/05/2012	01:00:00	9.552	8.067	85.045	88.903
17/05/2012	13:00:00	8.549	7.565	85.045	87.888
18/05/2012	01:00:00	8.047	7.565	84.531	89.912
18/05/2012	13:00:00	7.043	7.565	85.045	88.396
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19/05/2012	13:00:00	7.545	7.064	84.531	89.408
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21/05/2012	01:00:00	10.054	7.565	85.045	88.903
21/05/2012	13:00:00	10.556	8.067	84.531	88.903
22/05/2012	01:00:00	12.561	9.069	83.497	88.903
22/05/2012	13:00:00	14.065	9.57	84.015	90.414
23/05/2012	01:00:00	16.069	10.573	82.978	88.903
23/05/2012	13:00:00	16.57	11.074	83.497	87.888
24/05/2012	01:00:00	18.073	12.577	81.935	87.378
24/05/2012	13:00:00	18.073	13.078	82.457	87.378
25/05/2012	01:00:00	19.575	13.579	81.411	87.378
25/05/2012	13:00:00	18.574	13.579	82.457	86.867
26/05/2012	01:00:00	18.574	14.08	82.457	86.867
26/05/2012	13:00:00	18.073	14.08	82.457	86.867
27/05/2012	01:00:00	18.574	14.581	82.457	87.378
27/05/2012	13:00:00	18.574	14.581	82.457	86.867

28/05/2012	01:00:00	20.576	15.082	81.935	87.378
28/05/2012	13:00:00	19.575	15.082	81.935	87.378
29/05/2012	01:00:00	18.574	15.082	81.935	87.378
29/05/2012	13:00:00	16.069	14.08	81.411	87.378
30/05/2012	01:00:00	14.566	13.579	82.457	87.378
30/05/2012	13:00:00	13.063	13.078	83.497	88.396
31/05/2012	01:00:00	13.063	13.078	83.497	86.867
31/05/2012	13:00:00	12.561	12.577	82.978	87.888
01/06/2012	01:00:00	12.561	12.076	83.497	87.888
01/06/2012	13:00:00	12.06	12.076	83.497	87.378
02/06/2012	01:00:00	13.063	12.076	82.457	87.888
02/06/2012	13:00:00	12.561	11.575	83.497	88.396
03/06/2012	01:00:00	12.561	11.074	82.978	87.888
03/06/2012	13:00:00	11.559	11.074	83.497	87.888
04/06/2012	01:00:00	11.559	10.573	82.978	88.396
04/06/2012	13:00:00	10.556	10.072	83.497	87.888
05/06/2012	01:00:00	12.561	10.573	82.978	88.396
05/06/2012	13:00:00	12.06	10.072	83.497	87.888
06/06/2012	01:00:00	13.063	11.074	82.978	88.396
06/06/2012	13:00:00	13.063	11.074	82.978	87.888
07/06/2012	01:00:00	13.564	11.575	82.457	87.888
07/06/2012	13:00:00	13.063	11.575	84.015	87.378
08/06/2012	01:00:00	13.063	12.076	84.015	87.888
08/06/2012	13:00:00	13.063	12.076	82.978	87.888
09/06/2012	01:00:00	13.564	12.076	82.457	88.396
09/06/2012	13:00:00	14.065	12.577	82.457	88.396
10/06/2012	01:00:00	15.067	12.577	82.457	88.396
10/06/2012	13:00:00	13.564	12.577	82.457	88.396
11/06/2012	01:00:00	13.063	12.076	82.457	87.888
11/06/2012	13:00:00	12.561	11.575	82.978	87.888
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12/06/2012	13:00:00	11.559	11.074	83.497	88.396
13/06/2012	01:00:00	12.561	11.575	82.457	87.378
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14/06/2012	01:00:00	13.063	11.074	82.457	88.396
14/06/2012	13:00:00	13.063	11.575	82.978	87.888
15/06/2012	01:00:00	13.063	11.575	82.457	88.396
15/06/2012	13:00:00	12.06	11.074	82.457	88.396
16/06/2012	01:00:00	11.057	11.074	82.457	87.888
16/06/2012	13:00:00	10.556	11.074	84.531	88.396
17/06/2012	01:00:00	11.057	11.074	82.978	88.396
17/06/2012	13:00:00	11.057	11.074	82.978	88.396
18/06/2012	01:00:00	12.06	11.074	82.978	88.396
18/06/2012	13:00:00	12.561	11.074	83.497	88.396
19/06/2012	01:00:00	14.065	11.575	82.457	88.396
19/06/2012	13:00:00	13.564	11.575	82.978	88.396

20/06/2012	01:00:00	15.067	12.076	81.935	88.396
20/06/2012	13:00:00	14.566	12.076	82.457	88.396
21/06/2012	01:00:00	15.568	12.577	81.935	87.888
21/06/2012	13:00:00	14.566	12.577	82.978	87.888
22/06/2012	01:00:00	14.065	12.577	81.935	87.888
22/06/2012	13:00:00	14.065	12.577	82.457	87.888
23/06/2012	01:00:00	14.566	13.078	81.935	87.378
23/06/2012	13:00:00	14.065	13.078	82.457	88.396
24/06/2012	01:00:00	14.566	13.078	81.935	88.396
24/06/2012	13:00:00	14.065	13.078	82.457	86.867
25/06/2012	01:00:00	15.067	13.579	82.457	87.888
25/06/2012	13:00:00	14.566	13.078	82.457	87.888
26/06/2012	01:00:00	16.57	13.579	81.935	87.378
26/06/2012	13:00:00	16.57	13.579	81.935	86.867
27/06/2012	01:00:00	16.069	14.08	81.935	87.378
27/06/2012	13:00:00	15.568	14.08	81.411	87.888
28/06/2012	01:00:00	15.568	14.08	81.935	87.888
28/06/2012	13:00:00	15.067	14.08	82.457	87.888
29/06/2012	01:00:00	15.568	14.581	81.411	87.378
29/06/2012	13:00:00	15.568	14.08	81.411	87.888
30/06/2012	01:00:00	15.568	14.581	82.978	87.378
30/06/2012	13:00:00	15.067	14.08	82.457	87.888
01/07/2012	01:00:00	15.067	14.08	81.935	87.378
01/07/2012	13:00:00	15.067	14.08	82.457	88.903
02/07/2012	01:00:00	15.568	14.08	81.935	86.867
02/07/2012	13:00:00	14.566	14.08	81.935	87.888
03/07/2012	01:00:00	14.566	14.08	81.935	87.888
03/07/2012	13:00:00	15.067	14.08	82.978	86.867
04/07/2012	01:00:00	16.069	14.581	82.457	87.378
04/07/2012	13:00:00	16.069	14.581	81.935	87.378
05/07/2012	01:00:00	17.572	15.082	81.935	87.378
05/07/2012	13:00:00	17.071	15.082	81.935	86.867
06/07/2012	01:00:00	18.574	15.582	81.935	86.354
06/07/2012	13:00:00	18.574	15.582	81.935	87.378
07/07/2012	01:00:00	19.074	16.083	81.411	86.867
07/07/2012	13:00:00	17.572	16.083	81.935	87.378
08/07/2012	01:00:00	16.57	15.582	81.935	87.378
08/07/2012	13:00:00	15.568	15.082	82.457	86.867
09/07/2012	01:00:00	16.069	15.082	82.457	87.378
09/07/2012	13:00:00	15.568	14.581	82.457	87.378
10/07/2012	01:00:00	15.568	14.581	82.457	87.888
10/07/2012	13:00:00	14.566	14.08	82.457	87.378
11/07/2012	01:00:00	14.065	14.08	82.457	86.867
11/07/2012	13:00:00	13.564	13.579	82.457	87.888
12/07/2012	01:00:00	14.065	13.579	82.978	87.888
12/07/2012	13:00:00	14.065	13.579	82.978	87.888

13/07/2012	01:00:00	14.566	13.579	83.497	87.888
13/07/2012	13:00:00	14.065	13.078	82.978	86.867
14/07/2012	01:00:00	14.065	13.078	82.978	87.378
14/07/2012	13:00:00	13.564	13.078	83.497	87.888
15/07/2012	01:00:00	14.065	13.078	82.457	88.396
15/07/2012	13:00:00	13.564	13.078	82.978	88.396
16/07/2012	01:00:00	14.065	13.078	82.457	87.378
16/07/2012	13:00:00	14.065	13.078	82.978	87.888
17/07/2012	01:00:00	16.069	14.08	82.457	87.378
17/07/2012	13:00:00	15.568	13.579	82.978	87.888
18/07/2012	01:00:00	16.069	14.08	82.978	87.888
18/07/2012	13:00:00	15.067	14.08	82.978	87.378
19/07/2012	01:00:00	14.566	14.08	82.978	87.888
19/07/2012	13:00:00	14.065	13.579	82.457	87.888
20/07/2012	01:00:00	14.566	13.579	82.978	86.867
20/07/2012	13:00:00	14.065	13.078	82.978	87.378
21/07/2012	01:00:00	15.568	13.579	82.457	87.888
21/07/2012	13:00:00	14.566	13.078	82.978	87.378
22/07/2012	01:00:00	16.069	14.08	82.457	87.888
22/07/2012	13:00:00	16.069	14.08	82.978	87.888
23/07/2012	01:00:00	17.572	15.082	82.457	87.378
23/07/2012	13:00:00	17.572	15.582	82.457	87.378
24/07/2012	01:00:00	16.57	15.582	82.978	87.378
24/07/2012	13:00:00	16.069	15.582	81.935	87.888
25/07/2012	01:00:00	17.071	15.582	82.978	87.888
25/07/2012	13:00:00	17.071	15.582	81.935	86.867
26/07/2012	01:00:00	17.572	15.582	81.935	87.378
26/07/2012	13:00:00	17.071	15.082	81.411	87.888
27/07/2012	01:00:00	17.071	15.582	82.978	88.396
27/07/2012	13:00:00	16.069	15.082	82.457	87.378
28/07/2012	01:00:00	16.069	15.082	82.978	87.378
28/07/2012	13:00:00	15.568	14.581	82.457	87.888
29/07/2012	01:00:00	15.568	14.581	81.935	87.378
29/07/2012	13:00:00	15.067	14.581	82.978	87.888
30/07/2012	01:00:00	15.568	14.581	82.978	87.378
30/07/2012	13:00:00	14.566	14.08	82.978	87.888
31/07/2012	01:00:00	14.566	14.08	82.978	87.888
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01/08/2012	01:00:00	15.568	13.579	82.457	87.378
01/08/2012	13:00:00	16.069	14.08	82.978	87.378
02/08/2012	01:00:00	17.071	14.581	82.978	87.888
02/08/2012	13:00:00	16.57	14.581	82.457	88.396
03/08/2012	01:00:00	17.572	15.082	81.935	87.888
03/08/2012	13:00:00	16.57	14.581	82.457	86.867
04/08/2012	01:00:00	17.572	15.082	82.457	87.378
04/08/2012	13:00:00	17.572	15.082	82.457	87.888

05/08/2012	01:00:00	18.574	15.582	81.411	87.888
05/08/2012	13:00:00	18.073	15.582	81.411	86.867
06/08/2012	01:00:00	18.073	15.582	81.935	86.354
06/08/2012	13:00:00	17.572	15.582	82.457	87.378
07/08/2012	01:00:00	17.572	15.582	81.935	86.354
07/08/2012	13:00:00	17.071	15.582	81.935	87.378
08/08/2012	01:00:00	18.073	16.083	81.935	87.378
08/08/2012	13:00:00	17.572	15.582	81.935	87.378
09/08/2012	01:00:00	18.073	16.083	81.935	87.378
09/08/2012	13:00:00	17.071	15.582	81.411	88.396
10/08/2012	01:00:00	18.073	15.582	81.935	87.378
10/08/2012	13:00:00	17.572	15.582	82.457	86.867
11/08/2012	01:00:00	18.574	16.083	81.411	87.378
11/08/2012	13:00:00	17.071	15.082	81.935	87.378
12/08/2012	01:00:00	17.572	15.582	81.935	87.378
12/08/2012	13:00:00	17.071	15.582	81.935	87.378
13/08/2012	01:00:00	17.572	16.083	82.457	87.378
13/08/2012	13:00:00	17.071	16.083	81.935	87.378
14/08/2012	01:00:00	17.572	16.083	82.457	87.378
14/08/2012	13:00:00	17.572	16.083	82.457	87.378
15/08/2012	01:00:00	18.574	16.584	81.411	86.867
15/08/2012	13:00:00	17.572	16.083	82.457	87.378
16/08/2012	01:00:00	17.572	16.584	81.935	87.888
16/08/2012	13:00:00	16.57	16.083	82.457	87.378
17/08/2012	01:00:00	17.572	16.083	81.935	87.378
17/08/2012	13:00:00	17.071	16.083	81.411	87.378
18/08/2012	01:00:00	18.073	16.584	82.457	87.378
18/08/2012	13:00:00	18.574	16.584	81.935	86.354
19/08/2012	01:00:00	19.074	17.085	81.411	86.867
19/08/2012	13:00:00	18.574	16.584	81.935	87.378
20/08/2012	01:00:00	18.574	16.584	81.411	86.354
20/08/2012	13:00:00	17.572	16.083	81.935	87.378
21/08/2012	01:00:00	18.574	16.584	82.457	86.354
21/08/2012	13:00:00	17.572	16.083	81.935	87.378
22/08/2012	01:00:00	17.071	16.083	81.935	87.378
22/08/2012	13:00:00	16.57	16.083	82.457	87.378
23/08/2012	01:00:00	17.071	16.083	82.457	87.888
23/08/2012	13:00:00	16.069	15.582	82.457	88.903
24/08/2012	01:00:00	17.071	15.582	82.978	88.903
24/08/2012	13:00:00	16.57	15.582	82.457	86.867
25/08/2012	01:00:00	16.57	15.582	82.457	87.378
25/08/2012	13:00:00	16.069	15.082	82.978	87.888
26/08/2012	01:00:00	16.069	15.082	84.015	87.378
26/08/2012	13:00:00	14.566	14.581	82.978	88.396
27/08/2012	01:00:00	15.067	14.08	82.457	87.888
27/08/2012	13:00:00	14.566	14.08	82.978	88.396

28/08/2012	01:00:00	15.067	14.581	82.457	88.396
28/08/2012	13:00:00	14.566	14.08	83.497	88.396
29/08/2012	01:00:00	15.568	14.581	82.457	88.396
29/08/2012	13:00:00	15.067	14.08	82.978	88.396
30/08/2012	01:00:00	14.065	14.08	82.978	88.396
30/08/2012	13:00:00	13.063	13.579	82.978	88.396
31/08/2012	01:00:00	13.564	13.078	82.457	88.396
31/08/2012	13:00:00	11.559	11.575	83.497	88.903
01/09/2012	01:00:00	12.561	12.076	83.497	88.396
01/09/2012	13:00:00	14.566	13.078	82.978	88.396
02/09/2012	01:00:00	15.568	13.579	82.457	88.903
02/09/2012	13:00:00	15.568	13.579	82.978	87.378
03/09/2012	01:00:00	17.071	14.581	81.935	88.396
03/09/2012	13:00:00	16.57	14.581	82.457	87.378
04/09/2012	01:00:00	18.073	15.082	81.935	87.888
04/09/2012	13:00:00	17.071	15.082	82.457	87.888
05/09/2012	01:00:00	16.57	15.082	81.935	87.378
05/09/2012	13:00:00	15.067	14.581	82.457	87.378
06/09/2012	01:00:00	15.067	14.08	82.457	88.396
06/09/2012	13:00:00	14.065	13.579	82.978	87.888
07/09/2012	01:00:00	15.568	14.581	82.978	88.396
07/09/2012	13:00:00	16.069	14.581	82.978	88.903
08/09/2012	01:00:00	17.572	15.582	81.935	87.888
08/09/2012	13:00:00	17.572	15.582	82.457	87.888
09/09/2012	01:00:00	17.572	16.083	81.935	88.396
09/09/2012	13:00:00	16.069	15.082	82.457	88.396
10/09/2012	01:00:00	16.57	15.582	82.457	87.888
10/09/2012	13:00:00	16.069	15.582	82.457	88.396
11/09/2012	01:00:00	14.065	14.581	82.978	88.396
11/09/2012	13:00:00	12.06	13.579	82.978	88.396
12/09/2012	01:00:00	12.561	13.078	82.978	88.396
12/09/2012	13:00:00	12.06	12.577	83.497	88.396
13/09/2012	01:00:00	12.06	12.076	83.497	88.903
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14/09/2012	01:00:00	13.564	12.577	82.978	88.903
14/09/2012	13:00:00	13.564	12.577	82.457	88.396
15/09/2012	01:00:00	14.065	12.577	82.457	88.903
15/09/2012	13:00:00	13.564	12.577	82.978	88.903
16/09/2012	01:00:00	14.566	13.078	82.457	88.396
16/09/2012	13:00:00	14.566	13.579	82.978	88.396
17/09/2012	01:00:00	13.564	13.078	82.457	88.396
17/09/2012	13:00:00	12.561	12.577	84.531	87.888
18/09/2012	01:00:00	11.559	12.577	83.497	89.408
18/09/2012	13:00:00	10.556	11.575	83.497	88.396
19/09/2012	01:00:00	11.057	11.074	83.497	88.903
19/09/2012	13:00:00	10.054	10.072	82.978	89.408

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21/09/2012	01:00:00	10.556	10.573	83.497	88.396
21/09/2012	13:00:00	9.552	9.57	83.497	89.408
22/09/2012	01:00:00	10.054	9.57	83.497	89.912
22/09/2012	13:00:00	9.051	9.069	84.531	90.414
23/09/2012	01:00:00	10.054	9.069	82.978	89.408
23/09/2012	13:00:00	9.051	8.568	82.978	89.912
24/09/2012	01:00:00	10.054	9.069	82.978	90.414
24/09/2012	13:00:00	10.556	9.57	83.497	89.408
25/09/2012	01:00:00	10.556	9.57	82.978	89.408
25/09/2012	13:00:00	10.556	10.072	83.497	89.912
26/09/2012	01:00:00	11.559	10.573	82.978	88.903
26/09/2012	13:00:00	11.559	10.573	83.497	89.408
27/09/2012	01:00:00	12.561	11.074	82.978	89.408
27/09/2012	13:00:00	11.559	10.573	82.457	88.903
28/09/2012	01:00:00	12.06	11.074	83.497	89.408
28/09/2012	13:00:00	12.06	11.074	82.457	89.912
29/09/2012	01:00:00	12.06	11.074	82.457	88.903
29/09/2012	13:00:00	11.559	10.573	83.497	89.408
30/09/2012	01:00:00	12.06	11.074	82.457	88.396
30/09/2012	13:00:00	13.063	11.575	82.978	88.903
01/10/2012	01:00:00	13.564	11.575	82.978	88.396
01/10/2012	13:00:00	13.063	11.575	82.457	88.903
02/10/2012	01:00:00	12.06	11.575	82.978	88.903
02/10/2012	13:00:00	11.057	11.074	82.978	88.903
03/10/2012	01:00:00	11.057	11.074	82.978	89.408
03/10/2012	13:00:00	10.054	10.573	82.978	89.912
04/10/2012	01:00:00	10.556	10.573	82.978	88.903
04/10/2012	13:00:00	9.051	9.57	82.978	89.408
05/10/2012	01:00:00	10.054	9.57	83.497	88.903
05/10/2012	13:00:00	9.552	9.57	84.015	89.912
06/10/2012	01:00:00	10.054	9.57	83.497	89.408
06/10/2012	13:00:00	9.552	9.069	84.015	87.888
07/10/2012	01:00:00	9.552	9.069	82.978	88.903
07/10/2012	13:00:00	8.549	8.067	84.015	89.912
08/10/2012	01:00:00	10.054	8.568	83.497	89.408
08/10/2012	13:00:00	8.549	8.067	83.497	89.912
09/10/2012	01:00:00	9.051	8.067	83.497	89.408
09/10/2012	13:00:00	7.545	7.064	84.015	90.414
10/10/2012	01:00:00	8.047	7.565	83.497	88.396
10/10/2012	13:00:00	6.541	6.562	84.531	90.414
11/10/2012	01:00:00	8.549	7.064	84.015	90.414
11/10/2012	13:00:00	9.552	7.565	84.015	89.912
12/10/2012	01:00:00	10.556	8.067	83.497	89.912
12/10/2012	13:00:00	11.057	8.568	83.497	89.912

13/10/2012	01:00:00	10.054	9.069	84.531	89.408
13/10/2012	13:00:00	9.552	9.069	83.497	89.408
14/10/2012	01:00:00	10.054	9.069	83.497	89.912
14/10/2012	13:00:00	9.552	9.069	84.015	88.903
15/10/2012	01:00:00	9.051	9.069	83.497	89.408
15/10/2012	13:00:00	7.043	8.067	84.015	91.415
16/10/2012	01:00:00	7.043	7.565	83.497	89.912
16/10/2012	13:00:00	6.541	7.064	84.015	90.915
17/10/2012	01:00:00	6.541	7.064	84.015	90.414
17/10/2012	13:00:00	4.533	6.061	84.531	90.915
18/10/2012	01:00:00	6.039	6.562	84.531	90.414
18/10/2012	13:00:00	7.043	6.562	82.978	90.414
19/10/2012	01:00:00	8.549	7.064	84.015	89.408
19/10/2012	13:00:00	8.549	7.565	83.497	90.414
20/10/2012	01:00:00	9.051	7.565	83.497	89.912
20/10/2012	13:00:00	9.552	8.067	84.531	89.912
21/10/2012	01:00:00	9.552	8.067	83.497	89.408
21/10/2012	13:00:00	8.549	7.565	83.497	89.912
22/10/2012	01:00:00	9.552	8.067	82.978	89.912
22/10/2012	13:00:00	8.549	7.565	84.015	89.912
23/10/2012	01:00:00	9.051	8.067	83.497	89.912
23/10/2012	13:00:00	9.051	8.067	83.497	89.912
24/10/2012	01:00:00	10.054	8.568	83.497	89.912
24/10/2012	13:00:00	10.054	8.568	83.497	89.912
25/10/2012	01:00:00	11.057	9.069	83.497	89.912
25/10/2012	13:00:00	10.054	8.568	83.497	89.408
26/10/2012	01:00:00	8.549	8.067	83.497	89.912
26/10/2012	13:00:00	6.039	7.064	84.015	89.912
27/10/2012	01:00:00	5.035	6.061	84.531	90.915
27/10/2012	13:00:00	4.533	5.058	85.045	90.915
28/10/2012	01:00:00	5.537	5.559	84.531	90.915
28/10/2012	13:00:00	7.043	6.061	84.531	90.414
29/10/2012	01:00:00	7.545	6.562	84.015	90.414
29/10/2012	13:00:00	6.541	6.061	85.045	90.414
30/10/2012	01:00:00	6.039	6.061	84.015	90.915
30/10/2012	13:00:00	6.039	6.061	84.531	89.912
31/10/2012	01:00:00	7.545	7.064	84.015	90.414
31/10/2012	13:00:00	8.047	7.064	83.497	90.414
01/11/2012	01:00:00	6.541	7.064	84.015	90.414
01/11/2012	13:00:00	4.533	6.061	84.531	90.915
02/11/2012	01:00:00	5.035	5.559	85.045	89.912
02/11/2012	13:00:00	5.537	5.559	84.531	90.414
03/11/2012	01:00:00	5.537	5.559	84.531	90.414
03/11/2012	13:00:00	3.528	4.556	85.045	91.415
04/11/2012	01:00:00	4.031	4.556	86.07	90.414
04/11/2012	13:00:00	3.026	4.055	85.559	90.915

05/11/2012	01:00:00	4.533	4.055	85.045	90.915
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06/11/2012	13:00:00	6.541	4.556	85.045	90.915
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07/11/2012	13:00:00	9.552	7.064	84.531	89.912
08/11/2012	01:00:00	10.054	7.565	83.497	89.912
08/11/2012	13:00:00	9.552	8.067	84.015	89.912
09/11/2012	01:00:00	10.054	8.067	84.015	89.912
09/11/2012	13:00:00	9.552	8.568	84.015	89.912
10/11/2012	01:00:00	8.549	8.067	84.531	89.912
10/11/2012	13:00:00	7.545	7.565	84.531	89.912
11/11/2012	01:00:00	7.043	7.565	85.045	90.915
11/11/2012	13:00:00	5.537	6.562	85.045	90.414
12/11/2012	01:00:00	5.537	6.061	85.045	90.414
12/11/2012	13:00:00	4.031	5.058	85.045	90.915
13/11/2012	01:00:00	5.035	5.559	85.045	90.915
13/11/2012	13:00:00	8.549	6.562	85.045	90.414
14/11/2012	01:00:00	10.054	8.067	84.015	90.414
14/11/2012	13:00:00	9.552	8.067	84.015	91.415
15/11/2012	01:00:00	9.051	8.067	84.531	89.912
15/11/2012	13:00:00	7.545	7.565	85.045	89.408
16/11/2012	01:00:00	8.047	7.565	84.531	89.912
16/11/2012	13:00:00	7.545	7.565	85.559	89.912
17/11/2012	01:00:00	7.545	7.565	84.531	90.414
17/11/2012	13:00:00	6.541	7.064	84.531	90.414
18/11/2012	01:00:00	6.039	6.562	84.531	90.414
18/11/2012	13:00:00	5.035	6.061	85.559	89.912
19/11/2012	01:00:00	5.035	5.559	85.045	90.414
19/11/2012	13:00:00	6.541	6.061	85.559	90.414
20/11/2012	01:00:00	9.051	7.565	84.015	89.912
20/11/2012	13:00:00	9.051	7.565	83.497	90.414
21/11/2012	01:00:00	9.051	8.067	84.531	89.408
21/11/2012	13:00:00	8.047	7.565	85.045	90.414
22/11/2012	01:00:00	6.541	6.562	85.045	89.912
22/11/2012	13:00:00	7.043	7.064	85.559	89.912
23/11/2012	01:00:00	7.043	7.064	85.045	90.414
23/11/2012	13:00:00	6.541	6.562	85.045	89.912
24/11/2012	01:00:00	6.039	6.562	85.045	90.915
24/11/2012	13:00:00	4.031	5.559	85.559	90.915
25/11/2012	01:00:00	3.528	5.058	85.045	90.915
25/11/2012	13:00:00	4.031	5.058	85.559	89.912
26/11/2012	01:00:00	4.533	5.058	85.559	90.915
26/11/2012	13:00:00	4.533	5.058	85.559	91.415
27/11/2012	01:00:00	4.533	5.058	86.07	89.912
27/11/2012	13:00:00	4.533	4.556	86.07	90.915

28/11/2012	01:00:00	4.533	4.556	85.559	90.915
28/11/2012	13:00:00	3.528	4.055	86.07	91.415
29/11/2012	01:00:00	3.528	4.055	86.07	90.915
29/11/2012	13:00:00	2.524	3.553	85.559	91.415
30/11/2012	01:00:00	2.524	3.051	86.07	91.415
30/11/2012	13:00:00	2.021	2.549	86.58	90.915
01/12/2012	01:00:00	2.524	3.051	86.07	90.915
01/12/2012	13:00:00	2.524	2.549	86.58	91.415
02/12/2012	01:00:00	2.524	2.549	86.07	91.415
02/12/2012	13:00:00	1.519	2.048	86.07	90.915
03/12/2012	01:00:00	2.021	1.546	86.07	91.913
03/12/2012	13:00:00	1.519	2.048	86.58	91.913
04/12/2012	01:00:00	2.524	2.048	85.045	91.913
04/12/2012	13:00:00	2.524	2.048	86.07	91.415
05/12/2012	01:00:00	2.021	2.048	86.07	91.415
05/12/2012	13:00:00	1.519	2.048	86.58	91.415
06/12/2012	01:00:00	1.016	1.546	86.07	91.913
06/12/2012	13:00:00	0.513	1.044	86.58	91.415
07/12/2012	01:00:00	1.519	1.546	87.089	91.913
07/12/2012	13:00:00	1.519	1.546	87.596	91.415
08/12/2012	01:00:00	2.524	2.048	86.58	91.415
08/12/2012	13:00:00	2.524	2.048	86.58	91.913
09/12/2012	01:00:00	4.533	3.051	86.07	90.915
09/12/2012	13:00:00	5.537	3.553	86.07	91.415
10/12/2012	01:00:00	5.035	4.055	86.07	91.415
10/12/2012	13:00:00	4.031	3.553	86.07	91.415
11/12/2012	01:00:00	3.026	3.051	86.07	91.913
11/12/2012	13:00:00	1.519	2.549	85.559	91.415
12/12/2012	01:00:00	1.016	2.048	86.58	91.913
12/12/2012	13:00:00	0.011	1.546	87.089	91.415
13/12/2012	01:00:00	-0.995	1.044	87.089	92.41
13/12/2012	13:00:00	-2	0.542	87.596	91.913
14/12/2012	01:00:00	-1.497	0.542	87.089	92.905
14/12/2012	13:00:00	-0.492	0.542	87.596	92.41
15/12/2012	01:00:00	2.524	2.048	86.58	91.415
15/12/2012	13:00:00	3.528	2.549	86.58	91.415
16/12/2012	01:00:00	5.035	3.051	86.58	90.915
16/12/2012	13:00:00	5.035	3.553	85.559	90.915
17/12/2012	01:00:00	5.035	3.553	86.07	92.41
17/12/2012	13:00:00	5.035	4.055	85.559	90.915
18/12/2012	01:00:00	5.537	4.055	86.07	90.915
18/12/2012	13:00:00	5.035	4.055	86.07	91.415
19/12/2012	01:00:00	4.533	4.055	87.089	90.915
19/12/2012	13:00:00	4.533	4.055	86.07	90.915
20/12/2012	01:00:00	5.537	4.556	86.07	90.915
20/12/2012	13:00:00	5.537	5.058	86.58	91.415

21/12/2012	01:00:00	5.537	5.058	86.58	90.414
21/12/2012	13:00:00	5.537	5.058	86.58	90.915
22/12/2012	01:00:00	5.537	5.058	86.07	90.915
22/12/2012	13:00:00	5.537	5.559	86.07	91.415
23/12/2012	01:00:00	6.541	5.559	86.58	90.414
23/12/2012	13:00:00	7.043	6.061	86.07	90.915
24/12/2012	01:00:00	7.545	6.061	86.07	90.414
24/12/2012	13:00:00	7.043	6.061	86.07	90.414
25/12/2012	01:00:00	6.541	6.061	86.58	90.414
25/12/2012	13:00:00	4.533	5.058	86.07	91.415
26/12/2012	01:00:00	5.035	5.058	86.07	90.414
26/12/2012	13:00:00	5.035	5.058	86.58	90.915
27/12/2012	01:00:00	4.533	5.058	87.089	90.414
27/12/2012	13:00:00	3.528	4.556	86.58	89.912
28/12/2012	01:00:00	3.026	4.055	86.58	90.915
28/12/2012	13:00:00	3.026	3.553	86.07	90.414
29/12/2012	01:00:00	7.545	6.061	86.58	90.915
29/12/2012	13:00:00	8.549	6.562	86.07	90.414
30/12/2012	01:00:00	7.043	6.061	86.07	90.915
30/12/2012	13:00:00	5.035	5.559	86.58	90.915
31/12/2012	01:00:00	5.537	5.559	86.58	90.915
31/12/2012	13:00:00	8.047	6.562	86.58	90.414
01/01/2013	01:00:00	6.541	6.061	86.07	90.414
01/01/2013	13:00:00	5.035	5.559	86.58	90.915
02/01/2013	01:00:00	5.537	5.058	87.596	90.414
02/01/2013	13:00:00	5.537	5.058	86.07	90.915
03/01/2013	01:00:00	8.549	6.061	86.07	90.414
03/01/2013	13:00:00	9.552	7.064	86.07	90.414
04/01/2013	01:00:00	10.556	8.067	85.559	90.414
04/01/2013	13:00:00	10.556	8.568	85.559	89.912
05/01/2013	01:00:00	10.556	8.568	86.07	89.408
05/01/2013	13:00:00	10.054	8.568	86.07	89.408
06/01/2013	01:00:00	10.054	9.069	86.07	90.414
06/01/2013	13:00:00	8.549	8.067	86.58	89.912
07/01/2013	01:00:00	8.549	8.067	86.07	89.912
07/01/2013	13:00:00	8.549	8.067	86.58	89.912
08/01/2013	01:00:00	8.549	8.067	86.58	89.912
08/01/2013	13:00:00	9.051	8.067	86.07	89.408
09/01/2013	01:00:00	8.549	8.067	86.58	89.912
09/01/2013	13:00:00	6.541	7.064	87.089	89.408
10/01/2013	01:00:00	6.541	7.064	86.58	89.912
10/01/2013	13:00:00	4.533	6.061	87.596	91.415
11/01/2013	01:00:00	4.533	5.559	87.089	90.915
11/01/2013	13:00:00	4.031	5.058	87.596	90.414
12/01/2013	01:00:00	4.031	5.058	87.089	90.915
12/01/2013	13:00:00	3.528	4.556	87.089	91.913

13/01/2013	01:00:00	3.528	4.556	87.596	90.915
13/01/2013	13:00:00	2.524	4.055	87.596	91.415
14/01/2013	01:00:00	2.524	3.553	88.102	89.912
14/01/2013	13:00:00	2.021	3.553	88.102	90.915
15/01/2013	01:00:00	2.021	3.051	88.102	91.415
15/01/2013	13:00:00	1.519	3.051	88.606	90.414
16/01/2013	01:00:00	2.021	2.549	87.596	91.415
16/01/2013	13:00:00	1.016	2.048	88.102	91.913
17/01/2013	01:00:00	0.513	1.546	88.102	90.414
17/01/2013	13:00:00	0.513	1.546	88.606	91.415
18/01/2013	01:00:00	0.513	1.546	88.606	91.415
18/01/2013	13:00:00	1.016	1.546	88.606	91.415
19/01/2013	01:00:00	1.519	1.546	88.102	91.913
19/01/2013	13:00:00	1.519	2.048	88.606	92.41
20/01/2013	01:00:00	1.519	2.048	88.102	92.41
20/01/2013	13:00:00	1.519	2.048	88.102	91.913
21/01/2013	01:00:00	1.519	2.048	88.606	91.913
21/01/2013	13:00:00	1.519	2.048	88.102	90.915
22/01/2013	01:00:00	1.519	2.048	88.102	91.415
22/01/2013	13:00:00	1.519	2.048	88.102	91.415
23/01/2013	01:00:00	1.519	2.048	88.102	90.414
23/01/2013	13:00:00	1.519	2.048	88.102	92.905
24/01/2013	01:00:00	1.519	2.048	88.102	90.915
24/01/2013	13:00:00	1.016	2.048	88.102	91.415
25/01/2013	01:00:00	1.519	2.048	88.606	92.41
25/01/2013	13:00:00	1.519	2.048	88.606	91.913
26/01/2013	01:00:00	1.519	2.048	88.102	91.415
26/01/2013	13:00:00	1.519	2.048	88.606	91.415
27/01/2013	01:00:00	2.524	2.048	88.102	91.415
27/01/2013	13:00:00	4.031	2.549	88.102	91.415
28/01/2013	01:00:00	4.031	3.051	87.596	91.415
28/01/2013	13:00:00	4.533	3.553	88.606	90.915
29/01/2013	01:00:00	5.537	4.055	87.596	91.415
29/01/2013	13:00:00	6.541	4.556	88.102	91.415
30/01/2013	01:00:00	7.043	5.058	87.596	91.415
30/01/2013	13:00:00	6.541	5.559	87.089	90.915
31/01/2013	01:00:00	7.043	5.559	87.596	91.415
31/01/2013	13:00:00	6.039	5.058	87.089	90.915
01/02/2013	01:00:00	5.537	5.058	87.596	92.41
01/02/2013	13:00:00	5.537	5.058	87.596	92.41
02/02/2013	01:00:00	4.533	4.556	88.102	90.915
02/02/2013	13:00:00	3.026	3.553	88.102	90.414
03/02/2013	01:00:00	3.528	3.553	88.606	91.415
03/02/2013	13:00:00	5.035	3.553	88.102	90.915
04/02/2013	01:00:00	7.043	4.556	87.596	90.915
04/02/2013	13:00:00	6.039	5.058	87.596	91.415

05/02/2013	01:00:00	4.031	4.556	88.102	91.415
05/02/2013	13:00:00	3.026	4.055	88.102	90.414
06/02/2013	01:00:00	4.533	4.055	88.102	90.414
06/02/2013	13:00:00	3.528	3.553	88.606	91.415
07/02/2013	01:00:00	4.031	3.553	88.606	90.915
07/02/2013	13:00:00	3.026	3.051	88.102	90.915
08/02/2013	01:00:00	3.026	3.051	88.606	91.913
08/02/2013	13:00:00	3.528	3.051	88.606	91.415
09/02/2013	01:00:00	4.031	3.553	88.102	91.415
09/02/2013	13:00:00	4.031	3.553	89.109	91.415
10/02/2013	01:00:00	4.031	3.553	88.606	91.415
10/02/2013	13:00:00	3.528	3.553	88.606	91.415
11/02/2013	01:00:00	3.528	3.553	88.102	91.415
11/02/2013	13:00:00	3.528	3.553	88.102	91.415
12/02/2013	01:00:00	3.528	3.553	88.606	91.415
12/02/2013	13:00:00	3.528	3.553	88.606	91.415
13/02/2013	01:00:00	3.026	3.051	88.102	91.415
13/02/2013	13:00:00	2.524	3.051	89.109	90.915
14/02/2013	01:00:00	2.021	2.549	88.606	91.415
14/02/2013	13:00:00	2.524	3.051	89.109	91.913
15/02/2013	01:00:00	5.537	3.553	88.102	91.415
15/02/2013	13:00:00	5.537	4.055	89.109	91.415
16/02/2013	01:00:00	6.541	4.556	87.596	89.912
16/02/2013	13:00:00	5.035	4.055	88.606	90.915
17/02/2013	01:00:00	5.537	4.055	88.606	90.414
17/02/2013	13:00:00	6.039	4.556	88.102	90.915
18/02/2013	01:00:00	6.541	4.556	88.102	90.915
18/02/2013	13:00:00	4.533	3.553	88.606	91.415
19/02/2013	01:00:00	5.537	3.553	87.089	90.915
19/02/2013	13:00:00	3.528	3.051	88.606	91.913
20/02/2013	01:00:00	6.039	3.553	88.102	91.415
20/02/2013	13:00:00	6.039	3.553	88.606	91.415
21/02/2013	01:00:00	5.035	3.553	88.606	91.415
21/02/2013	13:00:00	4.031	3.553	88.606	91.415
22/02/2013	01:00:00	3.528	3.051	88.606	90.414
22/02/2013	13:00:00	2.524	3.051	89.61	90.915
23/02/2013	01:00:00	2.524	3.051	88.606	91.415
23/02/2013	13:00:00	2.021	2.549	89.109	91.913
24/02/2013	01:00:00	3.026	3.051	88.606	91.415
24/02/2013	13:00:00	2.524	2.549	88.606	91.913
25/02/2013	01:00:00	3.528	3.051	87.596	91.415
25/02/2013	13:00:00	2.524	2.549	88.606	91.913
26/02/2013	01:00:00	4.533	2.549	89.109	91.913
26/02/2013	13:00:00	3.528	2.549	88.102	91.913
27/02/2013	01:00:00	5.035	2.549	88.102	91.415
27/02/2013	13:00:00	3.528	2.048	88.606	91.913

28/02/2013	01:00:00	5.537	2.549	88.102	91.913
28/02/2013	13:00:00	4.533	2.549	88.606	90.915
01/03/2013	01:00:00	6.039	3.051	88.102	90.915
01/03/2013	13:00:00	5.035	3.051	88.606	91.415
02/03/2013	01:00:00	6.541	3.553	88.102	91.415
02/03/2013	13:00:00	6.039	3.553	88.606	91.913
03/03/2013	01:00:00	8.047	4.556	87.596	90.915
03/03/2013	13:00:00	7.545	4.556	88.102	91.913
04/03/2013	01:00:00	7.545	5.058	87.596	90.915
04/03/2013	13:00:00	6.541	5.058	88.102	90.915
05/03/2013	01:00:00	6.039	5.058	88.102	90.915
05/03/2013	13:00:00	4.533	4.055	88.102	91.913
06/03/2013	01:00:00	6.039	4.556	88.606	91.415
06/03/2013	13:00:00	5.537	4.556	88.606	91.415
07/03/2013	01:00:00	5.537	4.556	89.109	91.415
07/03/2013	13:00:00	5.537	5.058	87.596	90.414
08/03/2013	01:00:00	5.537	5.058	88.102	90.915
08/03/2013	13:00:00	5.035	5.058	88.606	91.415
09/03/2013	01:00:00	4.533	4.556	88.102	91.415
09/03/2013	13:00:00	4.031	4.556	88.606	90.915
10/03/2013	01:00:00	3.528	4.055	88.606	90.414
10/03/2013	13:00:00	3.026	3.553	89.109	91.415
11/03/2013	01:00:00	1.519	3.051	89.109	91.415
11/03/2013	13:00:00	0.513	2.048	89.61	92.41
12/03/2013	01:00:00	1.016	1.546	90.109	91.913
12/03/2013	13:00:00	1.016	1.044	89.109	92.905
13/03/2013	01:00:00	2.524	1.546	88.606	92.41
13/03/2013	13:00:00	2.021	1.546	89.109	91.913
14/03/2013	01:00:00	3.528	1.546	88.606	91.415
14/03/2013	13:00:00	2.524	1.546	89.109	90.915
15/03/2013	01:00:00	4.031	2.549	88.606	91.913
15/03/2013	13:00:00	5.035	3.051	88.606	91.415
16/03/2013	01:00:00	5.537	3.553	88.102	91.913
16/03/2013	13:00:00	3.528	2.549	88.606	91.913
17/03/2013	01:00:00	3.528	3.051	88.102	91.913
17/03/2013	13:00:00	3.528	3.051	88.606	91.415
18/03/2013	01:00:00	4.031	3.553	88.606	91.913
18/03/2013	13:00:00	4.031	3.553	88.606	91.415
19/03/2013	01:00:00	3.026	3.051	88.102	91.913
19/03/2013	13:00:00	2.021	2.549	89.109	91.913
20/03/2013	01:00:00	2.021	2.549	89.109	91.913
20/03/2013	13:00:00	2.021	2.549	88.606	91.415
21/03/2013	01:00:00	2.524	2.549	88.606	91.913
21/03/2013	13:00:00	2.021	2.048	89.109	91.913
22/03/2013	01:00:00	3.026	2.549	90.109	91.913
22/03/2013	13:00:00	2.524	2.549	89.109	92.41

23/03/2013	01:00:00	2.021	2.048	88.606	91.415
23/03/2013	13:00:00	1.519	2.048	89.109	91.415
24/03/2013	01:00:00	1.519	1.546	87.596	92.41
24/03/2013	13:00:00	1.519	1.546	89.61	92.905
25/03/2013	01:00:00	1.519	1.546	88.102	91.913
25/03/2013	13:00:00	1.519	1.546	89.61	93.398
26/03/2013	01:00:00	2.021	2.048	88.606	91.415
26/03/2013	13:00:00	2.021	2.048	88.606	92.905
27/03/2013	01:00:00	2.524	2.048	88.102	91.913
27/03/2013	13:00:00	2.524	2.048	89.109	91.913
28/03/2013	01:00:00	2.524	2.048	88.606	91.913
28/03/2013	13:00:00	2.021	2.048	89.109	91.913
29/03/2013	01:00:00	3.528	2.048	88.102	91.913
29/03/2013	13:00:00	2.524	2.048	89.109	90.414
30/03/2013	01:00:00	3.528	2.048	88.606	91.913
30/03/2013	13:00:00	2.524	1.546	89.61	91.415
31/03/2013	01:00:00	3.026	2.048	87.596	91.913
31/03/2013	13:00:00	2.021	1.546	88.606	92.41
01/04/2013	01:00:00	3.026	2.048	88.102	91.415
01/04/2013	13:00:00	2.524	1.546	89.109	91.913
02/04/2013	01:00:00	3.528	2.048	89.109	91.913
02/04/2013	13:00:00	3.026	2.048	89.109	92.41
03/04/2013	01:00:00	4.031	2.549	88.102	91.415
03/04/2013	13:00:00	3.026	2.048	88.606	91.913
04/04/2013	01:00:00	5.035	3.051	88.606	91.415
04/04/2013	13:00:00	5.035	3.051	88.102	91.415
05/04/2013	01:00:00	6.039	3.553	88.102	91.913
05/04/2013	13:00:00	5.537	3.553	88.606	91.415
06/04/2013	01:00:00	6.039	3.553	88.102	91.415
06/04/2013	13:00:00	5.035	3.051	87.089	91.415
07/04/2013	01:00:00	7.043	4.055	87.596	91.415
07/04/2013	13:00:00	6.039	4.055	88.102	91.415
08/04/2013	01:00:00	4.533	4.055	88.606	90.414
08/04/2013	13:00:00	4.031	4.055	88.606	90.915
09/04/2013	01:00:00	4.031	3.553	88.606	92.905
09/04/2013	13:00:00	4.031	3.553	88.102	90.915
10/04/2013	01:00:00	5.537	4.055	88.102	90.915
10/04/2013	13:00:00	5.537	4.055	88.102	91.415
11/04/2013	01:00:00	5.537	4.055	88.102	91.415
11/04/2013	13:00:00	5.035	4.556	88.102	91.415
12/04/2013	01:00:00	5.537	4.556	88.102	91.415
12/04/2013	13:00:00	5.035	4.556	89.109	90.414
13/04/2013	01:00:00	5.537	4.556	88.102	91.913
13/04/2013	13:00:00	5.035	4.556	88.102	90.414
14/04/2013	01:00:00	7.545	5.559	88.606	90.915
14/04/2013	13:00:00	10.054	7.064	87.596	90.414

15/04/2013	01:00:00	11.057	8.067	87.089	90.915
15/04/2013	13:00:00	11.057	8.568	87.089	90.915
16/04/2013	01:00:00	11.559	9.069	86.58	89.912
16/04/2013	13:00:00	10.556	9.069	86.58	89.912
17/04/2013	01:00:00	10.054	9.069	87.089	89.912
17/04/2013	13:00:00	8.549	8.067	87.089	90.915
18/04/2013	01:00:00	9.552	8.568	87.596	89.912
18/04/2013	13:00:00	9.552	8.568	87.596	90.414
19/04/2013	01:00:00	9.552	8.568	86.58	90.414
19/04/2013	13:00:00	8.549	8.067	86.58	89.912
20/04/2013	01:00:00	10.054	8.067	87.089	90.414
20/04/2013	13:00:00	9.552	7.565	87.596	91.415
21/04/2013	01:00:00	10.556	8.568	86.58	89.912
21/04/2013	13:00:00	9.552	8.568	87.089	89.912
22/04/2013	01:00:00	10.054	8.568	87.089	89.912
22/04/2013	13:00:00	9.051	8.067	87.089	89.912
23/04/2013	01:00:00	10.556	8.568	86.58	90.414
23/04/2013	13:00:00	10.556	8.568	87.089	90.414
24/04/2013	01:00:00	11.559	9.069	86.07	89.912

Appendix 4. Microwave moisture sensor (MMS) survey data

Appendix 4.1 Data recorded from sampling conducted across the north wall of the Old Schoolhouse, Cottown

Vertical distance from ground, cm	Horizontal distance from eastern end, cm	Relative moisture 28/11/2012, 0-4000	Relative moisture 17/01/2013, 0-4000	Relative moisture 20/03/2013, 0-4000	Relative moisture 24/04/2013, 0-4000	Mean relative moisture, 0-4000	Standard deviation of relative moisture measurements
220	0	1505	1350	1373	1355	1395.75	73.5
220	30	1043	1192	1436	1423	1273.5	190.2008
220	60	1305	1288	1592	1612	1449.25	176.7057
220	90	1521	1323	1197	1354	1348.75	133.4026
220	120	1320	1600	1490	1237	1411.75	163.8259
220	150	1244	1351	1392	1366	1338.25	65.0762
220	180	1247	1267	1547	1249	1327.5	146.6095
220	210	1445	1557	1368	1446	1454	77.7817
220	240	1279	1077	1458	1203	1254.25	159.3432
220	270	1258	1396	1389	1311	1338.5	66.0631
220	300	1200	1113	1604	1283	1300	214.2226
220	330	1264	1253	1211	1337	1266.25	52.4047
220	360	1291	1493	1352	1231	1341.75	112.2835
220	390	1218	1382	1454	1519	1393.25	129.5412
220	420	1230	1222	1317	1066	1208.75	104.4394
220	450	1361	1205	1302	1416	1321	90.2626
220	480	1321	1516	1383	1275	1373.75	104.6498
220	510	1430	1543	1229	1387	1397.25	130.0369
220	540	1399	1480	1296	1446	1405.25	80.0474
220	570	1600	1420	1151	1312	1370.75	188.6114
220	600	1458	1409	1377	1233	1369.25	96.7484
220	630	1253	1311	1682	1343	1397.25	193.4535
220	660	1367	1201	1221	1306	1273.75	77.0514
220	690	1200	1324	1504	1416	1361	130.082
220	720	1304	1404	1206	1378	1323	88.7619
220	750	1273	1462	1384	1419	1384.5	80.8888
220	780	1252	1236	1356	1372	1304	69.8952
220	810	1189	1414	1356	1092	1262.75	148.5112
220	840	1217	1177	1102	1211	1176.75	52.8544
220	870	1305	1295	1510	1253	1340.75	115.0605
220	900	1301	1427	1306	1343	1344.25	58.2602
220	930	1232	1065	1534	1085	1229	216.5379
220	960	1320	1316	1413	1219	1317	79.2254
220	990	1336	1386	1263	1213	1299.5	76.6572
220	1020	1089	1099	1305	1181	1168.5	99.8983

220	1050	1152	1160	1387	1314	1253.25	116.2279
220	1080	1370	1267	1210	1381	1307	82.5712
220	1110	1259	1360	1293	1403	1328.75	64.8916
220	1140	1527	1329	1259	1697	1453	198.3465
220	1170	1278	1282	1676	1367	1400.75	188.0343
220	1200	1310	1334	1265	1246	1288.75	40.3764
220	1230	1307	1299	1483	1451	1385	95.6382
190	0	1584	1244	905	1674	1351.75	350.7044
190	30	1444	1465	896	1312	1279.25	264.3222
190	60	1398	1457	1129	1167	1287.75	163.893
190	90	1421	1299	1205	1383	1327	95.9861
190	120	1568	1429	1224	1546	1441.75	157.464
190	150	1310	1230	1322	1419	1320.25	77.4699
190	180	1338	1299	1177	1403	1304.25	95.0627
190	210	1087	1521	1510	1451	1392.25	205.808
190	240	1227	1513	1294	1362	1349	122.4391
190	270	1283	1462	941	1394	1270	231.4087
190	300	1473	1550	1244	1352	1404.75	134.6338
190	330	1184	1504	1351	1410	1362.25	134.5025
190	360	1278	1362	1424	1494	1389.5	91.8314
190	390	1305	1368	1288	1291	1313	37.4077
190	420	1151	1336	1367	1378	1308	106.1665
190	450	1676	1281	1243	1227	1356.75	214.0348
190	480	1166	1231	1224	1395	1254	98.4107
190	510	1271	1193	1318	1470	1313	116.6733
190	540	1207	1526	1461	1533	1431.75	153.3001
190	570	1419	1398	1295	1316	1357	60.6905
190	600	1340	1352	1224	1481	1349.25	105.1011
190	630	1460	1246	1586	1408	1425	140.8025
190	660	1259	1099	1129	1212	1174.75	73.749
190	690	1430	1467	1372	1273	1385.5	84.5794
190	720	1281	1357	1295	1217	1287.5	57.4427
190	750	1171	1227	1300	1431	1282.25	112.3547
190	780	1445	1510	1554	1370	1469.75	80.1681
190	810	1181	1126	1306	1453	1266.5	145.3651
190	840	1276	1305	1165	1145	1222.75	79.5419
190	870	1148	1106	1015	1428	1174.25	178.0419
190	900	1446	1596	1001	1334	1344.25	252.756
190	930	1260	1369	1371	1396	1349	60.5915
190	960	1196	1218	1171	1085	1167.5	58.2552
190	990	1283	1494	1168	1349	1323.5	136.0649
190	1020	1377	1372	1166	1261	1294	100.7406
190	1050	1306	1547	1151	1415	1354.75	167.8102
190	1080	1184	1285	1214	1338	1255.25	69.5479
190	1110	1250	1334	1394	1387	1341.25	66.4699
190	1140	1285	1334	1285	1309	1303.25	23.4147

190	1170	1375	1440	1356	1504	1418.75	67.2576
190	1200	1265	1263	1327	1337	1298	39.48
190	1230	1230	1187	1226	1287	1232.5	41.1866
160	0	1268	1325	991	1326	1227.5	159.9802
160	30	1505	1313	1216	1298	1333	122.3356
160	60	1120	1136	1219	1077	1138	59.4699
160	90	1141	1296	1105	1509	1262.75	183.8956
160	120	1334	1387	1110	1227	1264.5	122.6282
160	150	1234	1376	1273	1145	1257	95.7253
160	180	1236	1383	1227	1423	1317.25	100.4204
160	210	1427	1337	1091	803	1164.5	279.7302
160	240	1232	1346	1201	1462	1310.25	118.8343
160	270	1209	1425	1444	1314	1348	108.9679
160	300	1176	1186	1106	1569	1259.25	209.5445
160	330	1039	1347	962	1380	1182	212.3503
160	360	1307	1251	1272	1295	1281.25	24.8512
160	390	1337	1501	1515	1320	1418.25	104.0236
160	420	1357	1480	1371	1470	1419.5	64.4696
160	450	1279	1494	1342	1263	1344.5	105.3391
160	480	1357	1392	1389	1159	1324.25	111.2995
160	510	0	0	0	0	0	0
160	540	0	0	0	0	0	0
160	570	0	0	0	0	0	0
160	600	1240	1764	1238	1205	1361.75	268.6465
160	630	1495	1406	1205	1462	1392	129.9667
160	660	1299	1179	1290	1168	1234	70.0999
160	690	1167	1226	1219	1225	1209.25	28.3358
160	720	1217	1495	1534	1221	1366.75	171.3561
160	750	1323	1224	1198	1320	1266.25	64.6858
160	780	1316	1126	996	1242	1170	139.8952
160	810	0	0	0	0	0	0
160	840	0	0	0	0	0	0
160	870	0	0	0	0	0	0
160	900	1322	1321	1114	1280	1259.25	98.7906
160	930	1261	1042	1072	1333	1177	142.1759
160	960	1325	1295	1070	1316	1251.5	121.6511
160	990	1367	1348	1109	1242	1266.5	118.5313
160	1020	1258	1369	1080	1223	1232.5	119.2043
160	1050	1315	1412	1094	1250	1267.75	133.5973
160	1080	1288	1411	1214	1256	1292.25	84.7678
160	1110	1257	1217	1095	1238	1201.75	73.0177
160	1140	1238	1330	1348	1191	1276.75	74.7591
160	1170	1310	1292	1177	1308	1271.75	63.6782
160	1200	1244	1279	1277	1312	1278	27.7729
160	1230	1352	1277	1235	1202	1266.5	64.7379
130	0	1226	1047	1388	1091	1188	153.5513

130	30	994	1237	1362	1011	1151	179.04
130	60	1130	1107	1426	952	1153.75	197.967
130	90	1046	1169	1457	1014	1171.5	201.7201
130	120	992	994	1450	1008	1111	226.1121
130	150	871	1085	1512	1041	1127.25	272.593
130	180	1185	1152	1415	1328	1270	123.2044
130	210	1109	1158	1381	1301	1237.25	125.7733
130	240	999	1095	1408	1183	1171.25	174.8073
130	270	837	1294	1311	1161	1150.75	219.6548
130	300	1174	1022	1102	1113	1102.75	62.4573
130	330	1075	1256	1399	1132	1215.5	143.788
130	360	1297	1423	1318	1275	1328.25	65.561
130	390	1343	1292	1075	1234	1236	116.2038
130	420	1254	1377	1145	1261	1259.25	94.7782
130	450	1285	1153	1190	1416	1261	117.34
130	480	1357	999	888	1274	1129.5	222.1028
130	510	0	0	0	0	0	0
130	540	0	0	0	0	0	0
130	570	0	0	0	0	0	0
130	600	1473	1445	1874	1514	1576.5	200.3472
130	630	1472	1660	1843	1409	1596	196.1717
130	660	1735	1765	2001	1308	1702.25	288.4988
130	690	1774	1826	1780	1245	1656.25	275.1489
130	720	1668	1670	1914	1233	1621.25	283.433
130	750	1276	1428	1582	1380	1416.5	127.2727
130	780	1100	1456	1501	1246	1325.75	187.0835
130	810	0	0	0	0	0	0
130	840	0	0	0	0	0	0
130	870	0	0	0	0	0	0
130	900	1249	1714	1517	1050	1382.5	292.3246
130	930	1165	1395	1453	1270	1320.75	128.8885
130	960	1174	1366	1588	1160	1322	200.6988
130	990	1031	1184	1622	1288	1281.25	250.492
130	1020	1079	1087	1496	1152	1203.5	197.7212
130	1050	1085	1067	1421	1211	1196	163.1073
130	1080	1075	1071	1460	1272	1219.5	185.7678
130	1110	1081	1210	1261	1252	1201	83.0301
130	1140	900	979	1692	1324	1223.75	362.4108
130	1170	996	1196	1481	1341	1253.5	207.3845
130	1200	1021	1073	1627	1339	1265	278.6396
130	1230	1064	1303	1597	1402	1341.5	221.6822
100	0	1125	1193	1753	1108	1294.75	307.6994
100	30	1258	1555	1643	1249	1426.25	202.7172
100	60	1266	1414	1609	1152	1360.25	197.4983
100	90	1305	1427	1565	1023	1330	230.5848
100	120	1223	1297	1802	1076	1349.5	315.3395

100	150	1305	1473	1755	1145	1419.5	260.6933
100	180	1220	1392	1761	1261	1408.5	246.1822
100	210	1166	1431	1723	1031	1337.75	305.8904
100	240	1218	1319	1316	1167	1255	75.1221
100	270	1233	1454	1653	1176	1379	218.4994
100	300	1227	1313	1717	889	1286.5	340.3816
100	330	925	1110	1000	1214	1062.25	126.5184
100	360	788	1252	1408	1280	1182	271.303
100	390	1146	1136	1126	1197	1151.25	31.574
100	420	1262	1114	1510	1047	1233.25	205.2046
100	450	1316	1195	1137	911	1139.75	169.7555
100	480	1042	1246	1465	1049	1200.5	200.0875
100	510	0	0	0	0	0	0
100	540	0	0	0	0	0	0
100	570	0	0	0	0	0	0
100	600	1505	1560	1413	1550	1507	67.0771
100	630	1430	1602	1596	1586	1553.5	82.5974
100	660	1414	1691	1725	1496	1581.5	150.4981
100	690	1354	1610	1682	1601	1561.75	143.1651
100	720	1701	1882	1729	1389	1675.25	206.7501
100	750	1355	1614	1527	1397	1473.25	119.0193
100	780	1329	1651	1606	1082	1417	264.8559
100	810	0	0	0	0	0	0
100	840	0	0	0	0	0	0
100	870	0	0	0	0	0	0
100	900	1261	1744	1473	1231	1427.25	237.049
100	930	1370	1658	1272	1208	1377	198.8266
100	960	1217	1817	1399	1221	1413.5	282.0703
100	990	1345	1602	1629	1680	1564	149.5393
100	1020	1246	1837	1444	1278	1451.25	271.4153
100	1050	1038	1813	1360	1118	1332.25	348.5096
100	1080	1147	1752	1005	1162	1266.5	331.307
100	1110	1333	1796	1279	1091	1374.75	299.3753
100	1140	890	1045	1086	1044	1016.25	86.4113
100	1170	1199	1492	1751	1308	1437.5	241.4574
100	1200	1274	1793	1671	1169	1476.75	301.9739
100	1230	1557	1788	1428	1292	1516.25	211.0172
70	0	1697	1549	1911	1281	1609.5	264.6576
70	30	1540	1393	1909	1255	1524.25	281.6634
70	60	1752	1780	1912	1132	1644	348.3906
70	90	1358	1657	2061	1283	1589.75	353.2717
70	120	1309	1690	1841	1256	1524	286.4111
70	150	1286	1919	1960	1202	1591.75	403.3562
70	180	1359	1879	1829	1423	1622.5	269.3616
70	210	1691	1954	1740	1238	1655.75	301.0032
70	240	1325	1818	1669	1321	1533.25	250.2857

70	270	1783	1836	1155	1425	1549.75	320.2784
70	300	1273	1703	1701	1135	1453	292.9892
70	330	1118	1364	1524	1293	1324.75	168.3199
70	360	1653	1689	1540	1494	1594	92.0543
70	390	1009	1532	1509	1212	1315.5	250.9774
70	420	1517	1727	1427	1183	1463.5	225.3198
70	450	1605	1746	1668	1310	1582.25	190.4422
70	480	1264	1485	1494	1122	1341.25	180.7713
70	510	1249	1854	1509	1332	1486	268.2275
70	540	1481	2047	1652	1364	1636	298.4326
70	570	1358	1923	1442	1260	1495.75	294.3834
70	600	1224	1814	1743	1181	1490.5	334.2758
70	630	1442	1707	1422	1554	1531.25	130.7756
70	660	1550	1889	1445	1414	1574.5	217.5937
70	690	1448	1846	1672	1415	1595.25	202.4341
70	720	1558	1746	1651	1419	1593.5	139.3712
70	750	1487	1726	1462	1385	1515	147.2119
70	780	1533	2081	1579	1292	1621.25	331.3351
70	810	0	0	0	0	0	0
70	840	0	0	0	0	0	0
70	870	0	0	0	0	0	0
70	900	1325	1786	1674	1334	1529.75	235.7348
70	930	1260	1923	1734	1430	1586.75	297.8158
70	960	1383	1999	1746	1333	1615.25	315.1533
70	990	1388	1735	1580	1387	1522.5	168.2389
70	1020	1396	1740	1456	1338	1482.5	178.2984
70	1050	1137	1786	1680	1255	1464.5	316.7275
70	1080	1390	1892	1716	1176	1543.5	321.3653
70	1110	1532	1716	1795	1225	1567	253.2285
70	1140	1030	1940	1855	1147	1493	470.7929
70	1170	1516	1987	1764	1386	1663.25	266.78
70	1200	1561	1923	1713	1309	1626.5	258.5156
70	1230	1388	1860	1626	1426	1575	216.7918
40	0	1710	1770	2037	1442	1739.75	244.1398
40	30	1758	1898	1896	1641	1798.25	123.6295
40	60	1520	2000	2004	1595	1779.75	258.4574
40	90	1663	2128	1994	1649	1858.5	240.2089
40	120	1743	1949	1954	1385	1757.75	267.2394
40	150	1698	2074	1980	1368	1780	317.7546
40	180	1540	1856	2011	1175	1645.5	369.8653
40	210	1372	2196	2158	1443	1792.25	445.4858
40	240	1494	1939	2123	1112	1667	454.5599
40	270	1496	2055	1389	1174	1528.5	375.6723
40	300	1590	1967	1536	1090	1545.75	359.2644
40	330	1797	1703	1459	1078	1509.25	320.8534
40	360	1472	2195	1558	1567	1698	334.0888

40	390	1367	1800	1680	1493	1585	192.5599
40	420	1752	1853	1200	1448	1563.25	297.1053
40	450	1439	1726	1477	1270	1478	188.2286
40	480	1688	1974	1624	1567	1713.25	180.7233
40	510	1473	1959	1572	1229	1558.25	303.5692
40	540	1310	1993	1181	893	1344.25	466.307
40	570	1597	2011	1568	1036	1553	399.6724
40	600	1421	1931	1693	1063	1527	372.9629
40	630	1429	1905	1539	1418	1572.75	228.1379
40	660	1483	2055	1949	1508	1748.75	295.7886
40	690	1460	1965	1797	1622	1711	218.2002
40	720	1465	2117	1785	1282	1662.25	367.588
40	750	1285	2234	1599	1278	1599	449.0219
40	780	1383	2099	1698	1370	1637.5	343.0107
40	810	1612	2025	1700	1265	1650.5	312.4063
40	840	1401	1935	1811	1549	1674	242.9293
40	870	1467	2017	1773	1436	1673.25	275.0398
40	900	1410	1842	1793	1196	1560.25	310.2734
40	930	1314	2038	1879	1162	1598.25	425.5635
40	960	1121	1879	1763	1265	1507	370.3512
40	990	1378	1835	1741	1105	1514.75	336.8208
40	1020	1528	2134	1870	1214	1686.5	400.9601
40	1050	1481	1960	1948	1256	1661.25	350.3307
40	1080	1290	2197	2191	1458	1784	478.3757
40	1110	1736	2080	1867	1470	1788.25	255.1684
40	1140	1234	1815	1821	952	1455.5	434.1294
40	1170	1344	1847	1868	1462	1630.25	266.9287
40	1200	1529	1845	1956	1368	1674.5	272.9011
40	1230	1488	1908	1517	1498	1602.75	203.8551
10	0	1745	1812	1985	1149	1672.75	363.5128
10	30	1633	1867	1952	1479	1732.75	216.3583
10	60	1624	2053	2225	1539	1860.25	331.2656
10	90	1891	1846	2201	1657	1898.75	225.5665
10	120	1579	2160	1608	1306	1663.25	358.0218
10	150	1696	1648	2117	1448	1727.25	281.154
10	180	1780	1907	2072	1459	1804.5	259.5079
10	210	1587	2415	2032	1009	1760.75	604.6864
10	240	1433	2110	1918	1325	1696.5	377.4869
10	270	1354	2222	1345	1261	1545.5	452.9404
10	300	1455	2114	1443	1437	1612.25	334.5837
10	330	1442	1923	1547	1274	1546.5	275.0327
10	360	1400	1850	1447	1405	1525.5	217.3576
10	390	1556	1999	1700	1392	1661.75	257.6488
10	420	1558	1949	1364	915	1446.5	429.8205
10	450	1328	2113	1578	1290	1577.25	379.3269
10	480	1132	1884	1338	1247	1400.25	333.333

10	510	1355	1830	1706	1381	1568	236.6615
10	540	1412	1848	1728	1590	1644.5	187.4487
10	570	1595	2076	1722	1576	1742.25	231.7475
10	600	1428	2136	1961	1045	1642.5	499.3332
10	630	1610	2105	1863	1430	1752	294.8322
10	660	1807	2076	1909	1493	1821.25	245.3221
10	690	1317	2048	2001	1334	1675	404.0833
10	720	1463	2151	1676	1455	1686.25	326.2998
10	750	1555	2396	2028	1018	1749.25	596.7821
10	780	1669	2040	1919	1269	1724.25	340.5538
10	810	1652	2166	2008	1409	1808.75	342.3929
10	840	1462	2083	1830	1433	1702	311.7189
10	870	1585	2443	1911	1680	1904.75	384.0593
10	900	1408	2204	1825	1372	1702.25	392.6274
10	930	1292	2170	2256	1226	1736	552.5673
10	960	1428	2375	2025	1472	1825	456.3325
10	990	1339	2358	1896	1657	1812.5	429.3115
10	1020	1489	2128	2034	1669	1830	301.4531
10	1050	1411	2235	2073	1175	1723.5	510.6502
10	1080	1321	2101	2033	1822	1819.25	352.7666
10	1110	1611	2408	1931	1592	1885.5	381.4748
10	1140	1510	2193	2159	1162	1756	505.5459
10	1170	1500	2191	2066	1466	1805.75	376.4132
10	1200	1610	2310	2295	1548	1940.75	418.5239
10	1230	1416	2260	2000	1314	1747.5	456.1531

Appendix 4.2 Data recorded from sampling conducted across the west wall of the Old Schoolhouse, Cottown

Vertical distance from ground, cm	Horizontal distance from northern end, cm	Relative moisture 28/11/2012, 0-4000	Relative moisture 17/01/2013, 0-4000	Relative moisture 20/03/2013, 0-4000	Relative moisture 24/04/2013, 0-4000	Mean relative moisture, 0-4000	Standard deviation of relative moisture measurements
250	0	937	1318	1027	980	1065.5	172.2992
250	30	1273	1582	1275	1293	1355.75	151.1012
250	60	1269	1361	1319	1254	1300.75	48.8424
250	90	1449	1210	1362	1351	1343	98.9107
250	120	1428	1456	1389	1382	1413.75	34.6831
250	150	1538	1394	1267	1223	1355.5	141.6298
250	180	1607	1435	1235	1290	1391.75	166.46
250	210	1664	1581	1342	1236	1455.75	200.2372
250	240	1640	1573	1279	1241	1433.25	202.5082
250	270	1623	1327	1375	1312	1409.25	145.0112
250	300	1601	1151	1421	1346	1379.75	186.2961
250	330	1577	854	1350	1350	1282.75	305.2074
250	360	1609	1336	1330	1306	1395.25	143.0883
250	390	1586	1373	1385	1196	1385	159.4428
250	420	1693	1409	1362	1284	1437	178.2825
250	450	1713	1425	1496	1172	1451.5	222.9985
250	480	1595	1357	1199	1237	1347	178.5198
250	510	1528	1375	1300	1334	1384.25	100.6193
250	540	1465	1489	1250	1429	1408.25	108.3432
250	570	1463	1392	1398	1299	1388	67.4833
250	600	1294	1481	1278	1171	1306	128.8125
250	630	1383	1431	1289	1365	1367	58.9915
250	660	1417	1266	1431	1480	1398.5	92.3706
250	690	1347	1459	1392	1428	1406.5	48.1975
220	0	1473	1314	1155	1242	1296	134.7219
220	30	1392	1319	1244	1263	1304.5	66.4555
220	60	1359	1438	1288	1213	1324.5	96.3276
220	90	1546	1321	1332	1397	1399	103.5793
220	120	1530	1134	1377	1396	1359.25	164.8825
220	150	1763	1490	1258	1420	1482.75	210.5887
220	180	1753	1242	1396	1190	1395.25	254.0333
220	210	1704	1353	1346	1416	1454.75	169.122
220	240	1613	1415	1409	1342	1444.75	116.9455
220	270	1772	1434	1437	1390	1508.25	177.141
220	300	1805	1229	1450	1419	1475.75	240.2601
220	330	1741	1388	1264	1298	1422.75	218.5214
220	360	1664	1288	1488	1454	1473.5	154.1547
220	390	1756	1363	1524	1528	1542.75	161.6114

220	420	1774	1437	1628	1430	1567.25	165.5685
220	450	1698	1498	1429	1456	1520.25	121.8534
220	480	1685	1537	1444	1552	1554.5	99.2522
220	510	1719	1508	1517	1349	1523.25	151.6056
220	540	1576	1578	1250	1196	1400	205.5691
220	570	1534	1603	1253	1360	1437.5	159.9469
220	600	1462	1484	1297	1246	1372.25	118.5253
220	630	1534	1445	1323	1293	1398.75	111.5837
220	660	1357	1544	1151	1252	1326	167.9147
220	690	1377	1596	1541	1319	1458.25	131.4214
190	0	1486	1393	1359	1336	1393.5	65.9621
190	30	1601	1342	1357	1404	1426	119.6188
190	60	1325	1264	1368	1233	1297.5	60.5778
190	90	1366	1033	1379	1209	1246.75	162.0954
190	120	1605	1502	1258	1374	1434.75	151.0395
190	150	1607	1182	1532	1483	1451	186.4421
190	180	1842	1297	1465	1433	1509.25	233.4843
190	210	1774	1495	1465	1396	1532.5	166.2498
190	240	1699	917	1571	1482	1417.25	345.1882
190	270	1831	1342	1531	1501	1551.25	204.1084
190	300	1775	1164	1402	1423	1441	251.7472
190	330	1851	1456	1440	1335	1520.5	226.7752
190	360	1767	1579	1482	1437	1566.25	146.3634
190	390	1761	1348	1481	1465	1513.75	175.1711
190	420	1621	1571	1540	1393	1531.25	98.0217
190	450	1556	1663	1436	1361	1504	132.9887
190	480	1603	1629	1411	1391	1508.5	124.8506
190	510	1686	1607	1377	1470	1535	138.0507
190	540	1595	1544	1370	1358	1466.75	120.5581
190	570	1207	1634	1331	1362	1383.5	179.9268
190	600	1426	1678	1420	1280	1451	165.6865
190	630	1297	1480	1435	1479	1422.75	86.419
190	660	1396	1551	1467	1357	1442.75	85.3322
190	690	1494	1520	1294	1515	1455.75	108.4201
160	0	1752	1486	1425	1449	1528	151.4265
160	30	1730	1493	1301	1490	1503.5	175.6901
160	60	1437	1299	1296	1263	1323.75	77.2415
160	90	1563	1296	1411	1294	1391	127.0407
160	120	1592	1066	1531	1300	1372.25	239.7921
160	150	1735	1039	1489	1454	1429.25	288.6525
160	180	1621	1371	1466	1423	1470.25	107.7447
160	210	1591	1069	1438	1420	1379.5	220.7601
160	240	1537	1159	1413	1471	1395	165.2876
160	270	1719	1190	1513	1351	1443.25	226.2364
160	300	1781	1199	1402	1364	1436.5	245.9898
160	330	1843	1594	1620	1327	1596	211.3055

160	360	1713	1546	1512	1360	1532.75	144.8433
160	390	1812	1548	1428	1418	1551.5	183.4366
160	420	1682	1756	1427	1389	1563.5	182.7393
160	450	1658	1655	1463	1395	1542.75	134.2544
160	480	1625	1806	1525	1424	1595	162.8517
160	510	1619	1798	1460	1321	1549.5	205.5926
160	540	1604	1743	1357	1341	1511.25	195.8645
160	570	1242	1694	914	999	1212.25	349.9508
160	600	1583	1492	1341	1352	1442	116.4503
160	630	1377	1655	1380	1265	1419.25	166.0289
160	660	1592	1816	1349	1290	1511.75	241.2943
160	690	1582	1697	1362	1441	1520.5	148.747
130	0	1623	1572	1433	1427	1513.75	98.9524
130	30	1500	1422	1475	1443	1460	34.4384
130	60	1685	1380	1498	1423	1496.5	134.7949
130	90	1766	1222	1231	1175	1348.5	279.4143
130	120	1530	917	1277	1144	1217	256.1887
130	150	1651	1117	1175	1126	1267.25	257.0997
130	180	1513	1282	1658	1181	1408.5	216.7402
130	210	1642	1056	1614	1511	1455.75	272.3874
130	240	1628	1129	1503	1388	1412	212.6045
130	270	1702	1083	1470	1300	1388.75	262.0984
130	300	1807	1379	1542	1466	1548.5	184.753
130	330	1809	1735	1500	1623	1666.75	134.9231
130	360	1731	1680	1598	1442	1612.75	126.3312
130	390	1770	1607	1485	1420	1570.5	153.9405
130	420	1649	1745	1561	1554	1627.25	89.6154
130	450	1630	1643	1500	1431	1551	102.804
130	480	1586	1804	1326	1446	1540.5	205.299
130	510	1599	1723	1369	1389	1520	170.6966
130	540	1498	1817	1510	1622	1611.75	147.789
130	570	1473	1777	1189	1310	1437.25	254.6427
130	600	1556	1414	1307	1331	1402	112.4366
130	630	1551	1755	1230	1254	1447.5	251.6724
130	660	1633	1857	1403	1628	1630.25	185.3562
130	690	1563	1790	1419	1498	1567.5	159.5922
100	0	1693	1797	1509	1430	1607.25	167.7585
100	30	1775	1665	1541	1326	1576.75	192.5658
100	60	1745	1730	1479	1503	1614.25	142.7851
100	90	1647	1687	1505	1420	1564.75	124.1407
100	120	1828	1586	1425	1374	1553.25	204.2374
100	150	1820	1746	1449	1540	1638.75	173.3116
100	180	1655	1433	1646	1435	1542.25	125.053
100	210	1709	1421	1644	1470	1561	137.4457
100	240	1616	1449	1525	1536	1531.5	68.335
100	270	1929	1341	1386	1222	1469.5	314.0494

100	300	1741	1490	1265	1261	1439.25	227.8631
100	330	1779	1670	1617	1621	1671.75	75.4514
100	360	1722	1904	1339	1524	1622.25	244.4155
100	390	1744	1861	1572	1399	1644	201.9059
100	420	1728	1949	1423	1472	1643	243.9276
100	450	1639	1861	1603	1436	1634.75	174.8492
100	480	1640	1804	1465	1418	1581.75	176.2884
100	510	1507	2010	1477	1373	1591.75	284.6839
100	540	1517	1781	1415	1324	1509.25	197.5759
100	570	1453	1773	1375	1340	1485.25	197.5624
100	600	1371	1989	1422	1442	1556	290.2103
100	630	1452	1940	1417	1387	1549	262.0165
100	660	1573	1969	1472	1470	1621	236.9318
100	690	1410	1818	1500	1320	1512	216.8317
70	0	1680	1957	1461	1218	1579	314.8174
70	30	1742	2000	1498	1294	1633.5	305.3495
70	60	1861	1841	1485	1334	1630.25	262.3755
70	90	1872	1816	1548	1395	1657.75	225.1139
70	120	1889	1589	1455	1294	1556.75	252.2041
70	150	1742	1953	1675	1519	1722.25	179.9803
70	180	1827	1606	1593	1562	1647	121.4111
70	210	1977	1774	1517	1470	1684.5	236.3846
70	240	2011	1564	1578	1412	1641.25	257.707
70	270	2027	1447	1556	1426	1614	281.1678
70	300	1983	1505	1384	1314	1546.5	301.5057
70	330	1898	1825	1550	1304	1644.25	271.8534
70	360	1811	1912	1650	1584	1739.25	149.5089
70	390	1798	1954	1346	1501	1649.75	276.2467
70	420	1662	1868	1342	1308	1545	267.9527
70	450	1638	1986	1436	1392	1613	270.7545
70	480	1558	1719	1559	1426	1565.5	119.8902
70	510	1556	1808	1374	1371	1527.25	206.1931
70	540	1640	1875	1352	1226	1523.25	291.572
70	570	1382	1856	1432	1346	1504	237.3015
70	600	1390	1894	1309	1271	1466	289.617
70	630	1485	2063	1386	1435	1592.25	316.4252
70	660	1460	2013	1502	1252	1556.75	323.2103
70	690	1573	1889	1458	1233	1538.25	273.161
40	0	1800	2071	2077	1281	1807.25	373.8631
40	30	1804	2297	1846	1490	1859.25	332.2643
40	60	1878	2336	1838	1155	1801.75	486.7706
40	90	1938	2269	1612	1680	1874.75	297.9926
40	120	1928	2194	1365	1588	1768.75	366.0067
40	150	1724	2309	1630	1408	1767.75	384.3873
40	180	1992	2037	1597	1394	1755	311.4365
40	210	1777	2162	1637	1560	1784	267.5307

40	240	1955	2324	1829	1628	1934	292.8037
40	270	2069	2106	1462	1281	1729.5	420.2067
40	300	1781	2097	1578	1271	1681.75	347.2572
40	330	1878	1638	1403	1291	1552.5	260.7636
40	360	2034	2272	1310	1456	1768	458.9408
40	390	1777	2173	1346	1433	1682.25	376.3875
40	420	1713	2331	1494	1523	1765.25	389.4718
40	450	1547	2008	1386	1459	1600	279.8512
40	480	1612	2023	1283	1204	1530.5	372.8525
40	510	1440	1831	1405	1440	1529	202.0083
40	540	1490	2160	1353	1662	1666.25	352.6078
40	570	1276	1956	1369	1431	1508	305.3839
40	600	1416	2026	1326	1357	1531.25	331.9391
40	630	1673	2122	1407	1420	1655.5	334.2359
40	660	1646	2176	1366	1496	1671	355.5747
40	690	1794	1966	1690	1302	1688	281.3776
10	0	1548	2032	1946	1455	1745.25	286.1694
10	30	1353	2365	1542	1290	1637.5	496.68
10	60	1527	2291	1993	1437	1812	401.6848
10	90	1806	2210	1957	1537	1877.5	281.6197
10	120	1801	2224	2074	1474	1893.25	329.8215
10	150	1631	2149	1884	1464	1782	299.4539
10	180	1947	2365	1877	1302	1872.75	437.263
10	210	2238	2308	1807	1323	1919	454.9146
10	240	1802	2063	1722	1706	1823.25	165.2581
10	270	2192	2253	1848	1498	1947.75	348.8365
10	300	2099	2179	1429	1434	1785.25	409.784
10	330	1833	2384	1687	1299	1800.75	449.4117
10	360	2034	2376	1654	1382	1861.5	434.9111
10	390	1913	2220	1212	1384	1682.25	466.3721
10	420	1842	2102	1456	1291	1672.75	367.7022
10	450	1671	2084	1580	1490	1706.25	262.4505
10	480	1595	2467	1506	1373	1735.25	496.2891
10	510	1553	1695	1372	1564	1546	132.7278
10	540	1560	1469	1801	1475	1576.25	155.4893
10	570	1541	2360	1786	1255	1735.5	469.4894
10	600	1760	2110	1614	1443	1731.75	283.4976
10	630	1781	2305	1499	1500	1771.25	379.7722
10	660	1590	2688	1674	1317	1817.25	600.1719
10	690	1861	2037	1891	1588	1844.25	187.3346

Appendix 5. Methodology for image analysis of thin sections

Capturing images[1]

- Set the microscope to 2X magnification
- Lock the light source >>> adjust ND filters and LBD to ensure appropriate greyscale.
- Take out one of the ND filters >>> apply XPL and ¼-wave plate
- Acquire and save images one by one, building up a suite for each thin section >>> return to these saved images to carry out image analysis

Image analysis

- Use tabs along the top of the screen – these flow in a logical order from left to right and vertically down each column
- Image >>> set colour thresholds >>> HIS >>> move hue, saturation and intensity to best fit the image >>> save as (this can then be opened for each analysis to ensure consistency)
- Analysis >>> define ROI >>> define measurements: AREA >>> define detection >>> frame (whole image) >>> pixel connectivity: 8
- Detect >>> results: single/particle
- Use particle sheet link to pinpoint a specific part of the image >>> delete rogue entries as appropriate

[1] Ensure that the same settings are used to capture each image.