British Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL

Geological notes for the Quaternary deposits of the Thetford District (1:50,000 Sheet 174)

Geology and Landscape

Internal Report IR/08/070

BRITISH GEOLOGICAL SURVEY

GEOLOGY AND LANDSCAPE
INTERNAL REPORT IR/08/070

Geological notes for the Quaternary deposits of the Thetford District (1:50,000 Sheet 174)

J R Lee, M D Bateman, H F Burke, S Hitchens, A Morigi, E Phillips

[1]British Geological Survey, Keyworth, Nottingham NG12 5GG; [2]Department of Geography, University of Sheffield, Sheffield S10 2TN; [3]British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA.

Keywords

Quaternary, Superficial, Thetford, East Anglia, coversand, periglacial, glaciation.

National Grid Reference

SW corner 569500,276320
NE corner 598660,295350

Map

Sheet 174, 1:50 000 scale, Thetford

Bibliographical reference

LEE, J R, BATEMAN, M D, BURKE H F, HITCHENS, S, MORIGI, A M, PHILLIPS, E. 2011. Geological notes for the Quaternary deposits of the Thetford District (1:50,000 Sheet 174). *British Geological Survey Internal Report*, IR/08/070. 37pp.

Keyworth, Nottingham British Geological Survey 2011

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276

email enquiries@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488

email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683

email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270

Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501

www.nerc.ac.uk

Website www.bgs.ac.uk

Shop online at www.geologyshop.com

Foreword

This report is the product of the recent geological survey of the Thetford District with the field survey undertaken between April 2007 and December 2008. The survey was supported by an extensive borehole and site investigation programme commissioned by the Environment Agency designed to supplement the field observations and enhance the spatial spread of geological information. The report is designed to provide an outline of the nature of the superficial geology of the survey District and should be used in conjunction with the published solid and drift Sheet 174 (British Geological Survey, 2010).

Acknowledgements

The authors of this report wish to thank the many landowners and land managers for granting access to enable the survey and the drilling programmes to be undertaken. Particular thanks are extended to Jim Broatch (Euston Estate), Jim Rudderham (Elveden Estate) and Tony Powell (Defence Estates – Stanford Military Training area) for their co-operation and assistance. Marc Amer, Joanna Brayson, Anna Harrison and Jo Venus and acknowledged for their logistical support. Don Aldiss, Brian Moorlock, Julian Murton, Frank Nicholson, Jim Rose and Mark Woods are thanked for their discussions regarding the geology of the Thetford District, whilst Frank Nicholson is kindly thanked for allowing us to use his patterned ground maps.

Contents

FIGURES

TABLES

Table 1. Status of 1:50,000 geological sheets in northern East Anglia. The ‘Modern Map’ category refers to maps surveyed using modern geological and cartographic approaches, with the ‘Modern SE/SD’ referring to the existence of either a modern Sheet Explanation of Sheet Description. * Fakenham and Swaffham are published as ‘Provisional’ maps.

Table 2. Lithostratigraphy of superficial deposits within the Thetford District.

Summary

This report provides an overview of the superficial geology of the Thetford District based upon the resurvey of Sheet 174 between 2007-2008 and should be used in conjunction with the newly published 1:50,000 geological map:

BRITISH GEOLOGICAL SURVEY. 2010. Thetford. England and Wales Sheet 174, Bedrock and Superficial Deposits. 1:50 000. Keyworth, Nottingham, British Geological Survey.

The superficial geology of the Thetford District provides a record of environmental change that has taken place in Eastern England over the past 2.6 million years. Prior to glaciation during the Middle Pleistocene, the District consisted of Chalk Downs dissected by a major river system – called the Bytham River, which extended eastwards from the West Midlands into East Anglia and the North Sea. At this time, the Bytham was probably one of the largest river systems of Southern Britain. Around Thetford, evidence for this river is preserved within a series of quartzose-rich gravels and a major buried valley that extends along the southern sheet boundary. During the Middle Pleistocene, the region was glaciated. Not only did this glaciation deposit extensive tracts of till (boulder clay) across Eastern England, but it destroyed the Bytham River system and excavated the Fen Basin leading to the generation of the modern drainage network. Compared to the rest of East Anglia, comparatively little till was deposited within the Thetford District suggesting that the area was one of net erosion beneath the Middle Pleistocene ice sheet. The District lay beyond the limit of later glaciations, but was none-the-less, strongly affected by cold climate processes that acted to disrupt the upper horizons of the Chalk bedrock and deposit extensive sheets of aeolian sediment (coversand). Since the end of the last Ice Age, humans have had a progressively more intrusive impact on the environment. Changes in land-use and management, as well as millennial-scale climatic oscillations, have led to major changes in geography and geological processes. For instance river channel migration and incision, reactivation of coversand sheets (‘sand blows’), and the construction of artificial ground. This also serves to highlight the degree of interaction between humans and the environment, and the value of understanding geology in order to protect and manage our natural resources and heritage.

1 Introduction

1.1 BACKGROUND

The Thetford 1:50,000 geological map sheet (Sheet 174) covers an area of approximately 575 km^2 that straddles the Norfolk and Suffolk borders in the west of East Anglia to the southwest of Norwich (Figure 1). Much of the sheet area forms a unique and distinctive landscape known as the 'The Brecks'. It consists of gently undulating relief dominated by chalky and sandy soils with forested deciduous and coniferous woodland and open expanses of heath. The region is drained by the Little Ouse, an east-bank tributary of the Great Ouse, and drains broadly east to west across the map sheet before entering the flat, low-lying region of the Fens between Lakenheath and Hockwold on the western edge of the sheet. Flowing into the Little Ouse are several smaller tributaries including the River Thet and the Black Bourne (Figure 2).

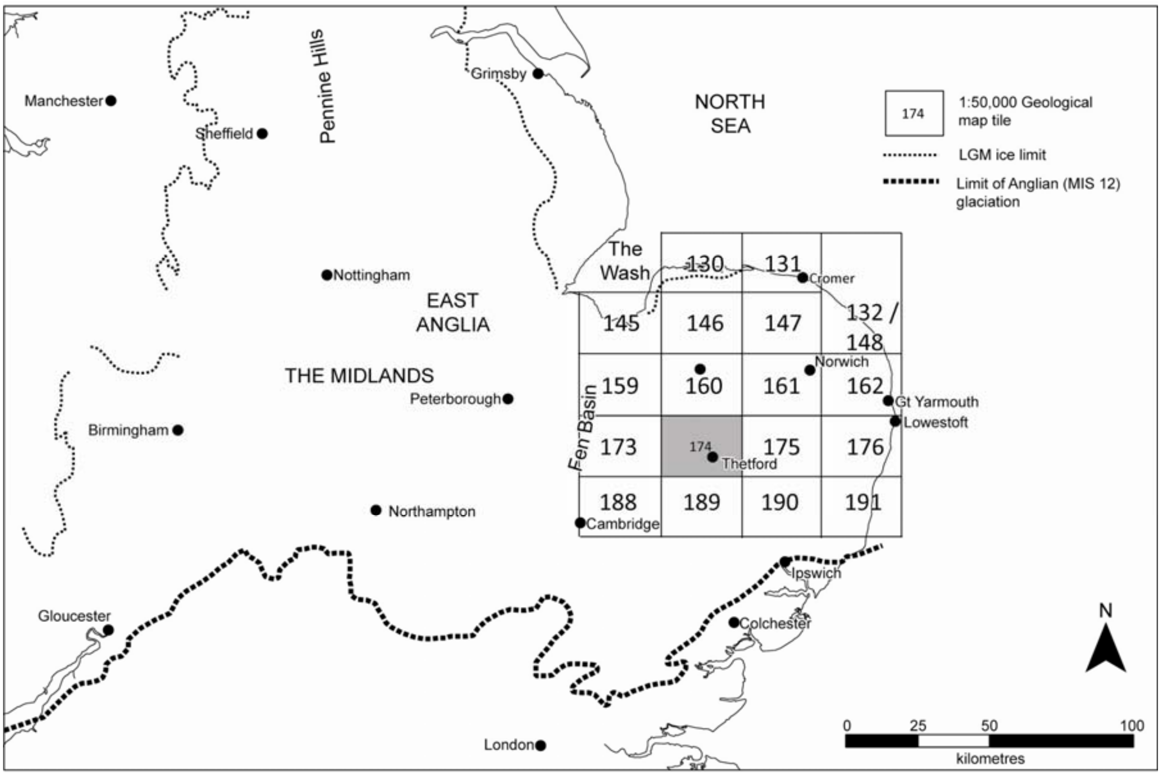

Figure 1. Map of central and eastern England showing 1:50,000 geological map tiles in northern East Anglia. The Thetford 1:50,000 map (Sheet 174) is highlighted in grey. Also shown are the main Middle (Anglian) and Late Pleistocene (Last Glacial Maximum) ice limits.

The Thetford District is largely rural with the principal land-uses being agriculture, forestry and military. The largest population centres of the District are the market towns of Thetford and Brandon which support mainly agricultural production and light manufacturing. Much of the agriculture land-use of the District is arable and the superficial geology has major implications for soil management especially as the Breckland soils are highly susceptible to deflation. Sustainable management of water resources and groundwater are of crucial important to the Thetford District as the area lies within one of the driest regions of Britain. However, knowledge of groundwater resources are somewhat restricted due to the poorly-understood nature and distribution of the superficial cover overlying the Chalk aquifer, and the form of the rockhead surface. In addition to current domestic and agricultural usage, increased pressure and demand for water is anticipated in light of the continued expansion of Lakenheath United States Air Force base, and the recent prioritisation of Thetford as one of the key centres for economic and residential growth in the Eastern region with 6000 new homes planned for the town by 2021. Unstable ground conditions are an additional geotechnical consideration for planners and engineers within the Thetford District. This hazard is associated with the karstification of the Chalk bedrock surface, especially in areas covered by coversand deposits and can lead in some instances to the localised collapse or subsidence of infrastructure. Again, knowledge of the distribution of coversand and karst features is poorly understood.

Up-to-date geological maps and assessments for the Thetford District are therefore crucial to assist decision makers and planners in the successful management and development of the natural resources and environment of the region. Within this report, we assess the quality of the 'Old Series' geological map, outline the principal geological surveying methodology, and provide an overview of the superficial geology of the area

1.2 SURVEY HISTORY

The first geological survey of the Thetford District was undertaken at 1:63,000 scale by F J Bennett and S B J Skertchly between 1875 and 1883. The results of the survey were published as four separate Old Series Sheets – 50NW (1882), 51NE (1883), 66SW (1884) and 65SW (1886), that span 'The Brecks' and the Fen Margin and an accompanying memoir (Whitaker *et al*., 1881).

Several partial resurveys of the Thetford District have occurred since the early published maps of Bennett and Skertchly and all utilise the modern National Grid. Parts of TL79 were resurveyed at 1:10,560 scale by R W Gallois and M C McKeown during the construction of the Little Ouse flood alleviation scheme between 1968-69. Between 1978 and 1979, parts of TL77, TL87 and TL87 were resurveyed by C R Bristow, T E Lawson, B S P Moorlock and C J Wilcox as part of the overlap with the Bury St Edmunds sheet (Sheet 189) to the south. In 1985 parts of TL98 and TL99 were resurveyed by S J Mathers and J A Zalasiewicz at 1:10,000 scale as part of the overlap with adjoining Diss sheet (175) to the east. Geological notes for the overlap are available from Mathers (1988).

During the 1970s and 1980s, much of central East Anglia was surveyed for mineral aggregates and one report covers the southern part of the Thetford District (Clayton, 1983).

The modern geological survey extended across the whole the Thetford Sheet with resurveying occurring at 1:10,000 scale. The superficial geology was mapped by H F Burke, J R Lee, A N Morigi and E Phillips, with contributions from M D Bateman, S Hitchens and F H Nicholson on the coversand and periglacial phenomena, and J Rose on the older fluvial superficial deposits.

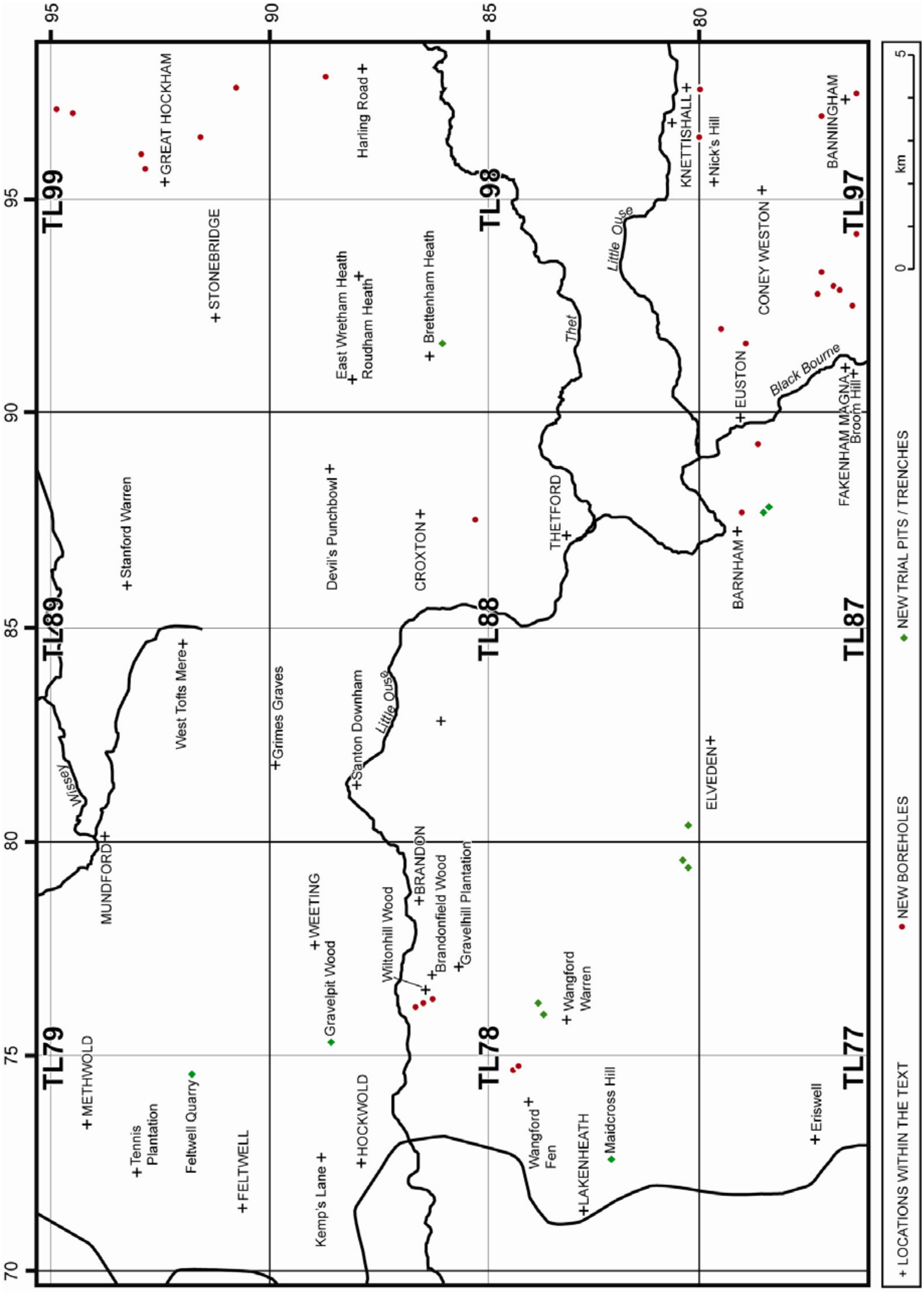

Figure 2. Map of the area covered by the 1:50,000 geological map sheet for the Thetford District showing the Ordnance Survey quarter sheet tiles and sites referred to within the text. Also shown are new boreholes (red dots) and new trial pits and trenches (green diamond) utilised during the survey.

1.3 OVERVIEW OF THE SUPERFICIAL GEOLOGY

The superficial geology of the Thetford District records a long and dynamic landscape history including evidence for prolonged and deep weathering, pre-glacial and post-glacial river systems, periglacial aeolian activity and freeze-thaw, and multiple changes in human land-use.

The oldest superficial deposits relate to the Ingham Formation (Lewis, 1993). These deposits are fluvial sands and gravels that were deposited by a major river system called the Bytham River that flowed along the western and southern margins of the District prior to the Anglian Glaciation during the Early and early Middle Pleistocene (2.6-0.45 Ma BP) (Rose *et al*., 2001). Along the present Norfolk and Suffolk borders, this river system incised a large river valley and part of its northern flank can be recognised within the District. There is no surface expression of this ancient river valley, as the river was overridden and destroyed by glaciers during the Anglian Glaciation which resulted in the infilling and burial of the palaeo-topography. During the Early and early Middle Pleistocene, the District possessed a Chalk Downlands – type landscape, and was subjected to numerous small oscillations in climate from temperate to cold conditions that had marked effects on flora, fauna and physical landscape processes (e.g. freeze-thaw, soil accretion etc) (Kemp *et al*., 1993).

About 600 ka BP the District underwent its first glaciation or Ice Age, and the Bytham River valley in East Anglia lay adjacent to the margins of the first lowland expansion of the British Ice Sheet during the Quaternary - this glaciation is referred to as the Happisburgh Glaciation (Lee *et al*., 2002, 2004). Evidence for this glaciation is represented by deposits of the Happisburgh Glacigenic Formation which are partially preserved within the buried Bytham River valley and include till (boulder clay) – the Starston Till, and glacial outwash sands and gravels called the Coney Weston Sands and Gravels.

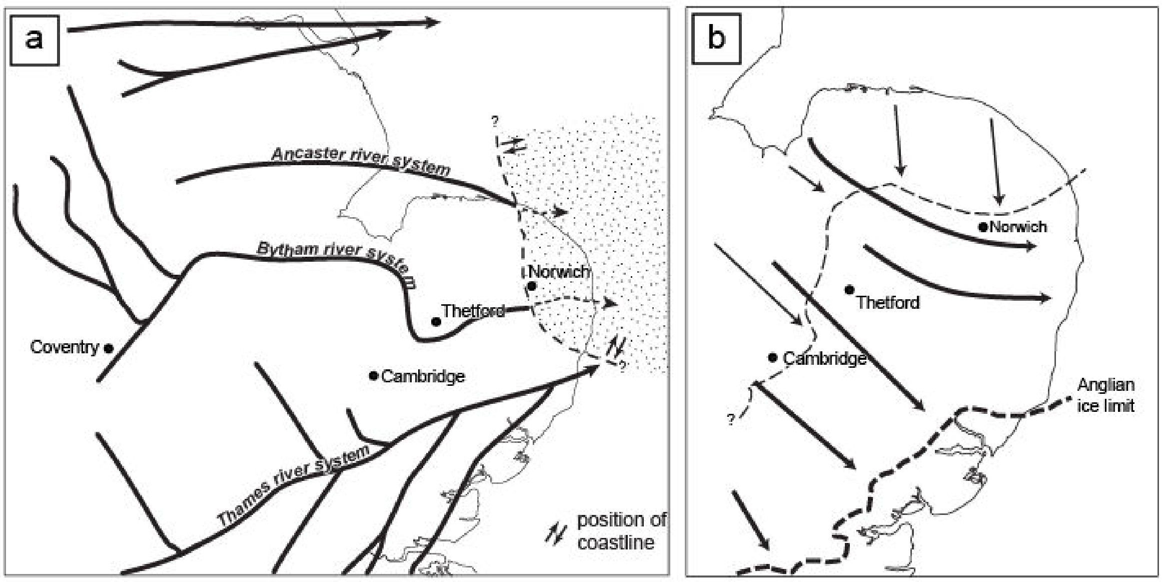

Figure 3. Palaeogeographic maps of central and eastern England during parts of the Quaternary. (a) Pre-glacial river systems and the position of the North Sea coast (after Rose *et al*., 2001); (b) the Anglian Glaciation in East Anglia – the arrows show the direction of flow of the British Ice Sheet across the region.

Between the Happisburgh Glaciation and the Anglian Glaciation, which followed 150,000 years later (450 ka BP), East Anglia underwent some dramatic climate changes.

Climate oscillated between Mediterranean-type temperate climates and periods where the permafrost developed and Southern Britain experienced tundra climates. Archaeological evidence from sites such as High Lodge and Warren Hill located to the south within the Bury St Edmunds District demonstrates that early Palaeolithic humans occupied the Bytham River valley during amenable climates (Wymer, 1985; Ashton *et al*., 1992).

The second and more extensive glaciation to affect the District was the Anglian Glaciation. This glaciation was the largest and most extensive to affect Britain during the Quaternary, with ice from highland areas of Britain extending as far south as the Cotswolds and present north London. This glaciation destroyed the Bytham River system, re-routed the lower reaches of the Ancestral Thames (Rose *et al.*, 2001) and caused widespread glacial erosion that included the creation of the Wash and Fen Basins and lowering of the Chalk escarpment (Clayton, 2000). Other distinctive products of the Anglian Glaciation in East Anglia include the presence of extensive networks of buried 'tunnel valleys' deeply incised into Chalk bedrock by subglacial meltwater (Woodland, 1970), and the deposition of vast tracts of glacial till and outwash sand and gravel (Perrin *et al*., 1979). Within the Thetford District, the affects of the Anglian Glaciation appear to have been largely erosional, with the scouring of deep buried 'tunnel valleys' by subglacial meltwater streams and the lowering of the chalk surface by subglacial erosion. Whilst some till – the Lowestoft Till, was deposited, much of this is now only preserved within lows in the Chalk surface such as the concealed valleys. Upon wastage of the British Ice Sheet, a series of small glaciolacustrine basins developed within the District and are recorded by the Lodge Farm Silts and Clays, and wider spreads of coarse grained glaciofluvial outwash.

Following deglaciation, a major climatic amelioration occurred resulting in the Hoxnian Interglacial. This interglacial occurred approximately 380 ka BP, and at its climatic optima, the climate of the District was Mediterranean in nature (Candy *et al*., 2010). Several of the largely infilled tunnel valleys acted as areas of low relief and roots for localised drainage. One of these streams and small valleys has been reconstructed linking the present-day villages of Barnham and Elveden and finds of Palaeolithic stone artefacts and butchered bones suggest that ancient humans lived within the landscape (Ashton *et al*., 1994, 2005).

Further development of drainage within the Thetford District following the Anglian Glaciation has continued to the present day with the establishment of the Little Ouse and its tributaries The Thet and the Black Bourne. Interestingly, prior to glaciation drainage across the District was broadly aligned west to east along the Bytham River valley that extended eastwards into the North Sea. Following this glaciation, drainage within the District flows westwards although the regional drainage-divide lies just beyond the eastern boundary of the sheet.

Following the Anglian Glaciation, the District was not glaciated again although during the Devensian cold stage (110 - 12 ka BP) the area lay just beyond the southern limits of the British Ice Sheet. During this interval and the early Holocene, the District was strongly affected by periglacial processes that resulted in that deposition of vast tracts of aeolian sediment ('coversand') (Perrin *et al*., 1974; Catt, 1977; Hoare *et al*., 2002; Bateman and Godby, 2004) and the breakdown and weathering of the chalk by freeze-thaw and frost heave (Williams, 1964; Watt *et al*., 1966).

Post-Anglian deposits within the Thetford area largely correspond to the development of a post-glacial drainage network superimposed upon this new landscape, and the *in situ* weathering and breakdown of surficial deposits under a period of dramatic climate change. The terrace deposits of the Little Ouse and its tributaries – The Thet and the Black Bourne, reflect the re-establishment of a broad east to west drainage pattern across the Thetford region.

2 Mapping Strategy and Methodologies

2.1 ASSESSMENT OF THE 'OLD SERIES' GEOLOGICAL MAP

The first geological map of the Thetford District was surveyed between 1875 and 1883 at 1:63,360 (1" inch to1 mile scale) and published as part of the 'Old Series' Sheets 51NE / NW. By modern geological surveying standards, the survey was completed at considerably lower resolution and without the aid of modern cartography or spatial positioning equipment (e.g. GPS). The 'Old Series' geological map shows the surface geology of the District to be dominated by Chalk bedrock with elevated ground to the north and south of the Little Ouse mantled by an extensive drape of chalky till (boulder clay) with minor pockets of glaciolacustrine silts and clays and glacial outwash sand and gravel (Figure 4). Small spreads of river terrace sand and gravel were recorded sporadically along the valley of the Little Ouse with the modern floodplain underlain by 'alluvium'.

In the early stages of the modern geological survey it became clear that the positioning of the superficial geology on the 'Old Series' geological map, and especially the geological boundaries, were highly erroneous. A prime example is the distribution of the till which on the 'Old Series' map was shown to be fairly extensive across the eastern and southern sides of the District. In many cases it was impossible to justify either the occurrence and / or positioning of the till outcrops based upon field evidence including auger hole data, soil observations and borehole records. Data collected as part of the modern geological survey demonstrate a more limited occurrence of till approximately 50% of that recorded by the 'Old Series' survey. It was concluded that during the 'Old Series' survey, the geologists greatly over-estimated the volume and extent of the till and in all probability, had great difficulty in distinguishing the till from weathered Chalk. In many respects this is understandable, as the original geologists did not have the benefit of hand-held augers which are one of the primary mapping tools for the modern field geologist mapping superficial terrain, and instead, relied largely upon observations made on soil composition. A further significant difference between the modern geological map and the 'Old Series' map, is the mapping of an extensive sheet of coversand across much of the District not shown by the original map. The existence of a coversand sheet within the Thetford District and much of the Brecks has been documented in historical records extending back several hundred years and more recent work by the Soil Survey and a number of scientific researchers. However, although observations of coversand throughout the British Isles are often recorded by field geologists, this has often not been consistently displayed upon the published geological map. On the modern map coversand has been shown where it has a thickness of greater than 1 m because it has important implications regarding soil management and various ground stability issues.

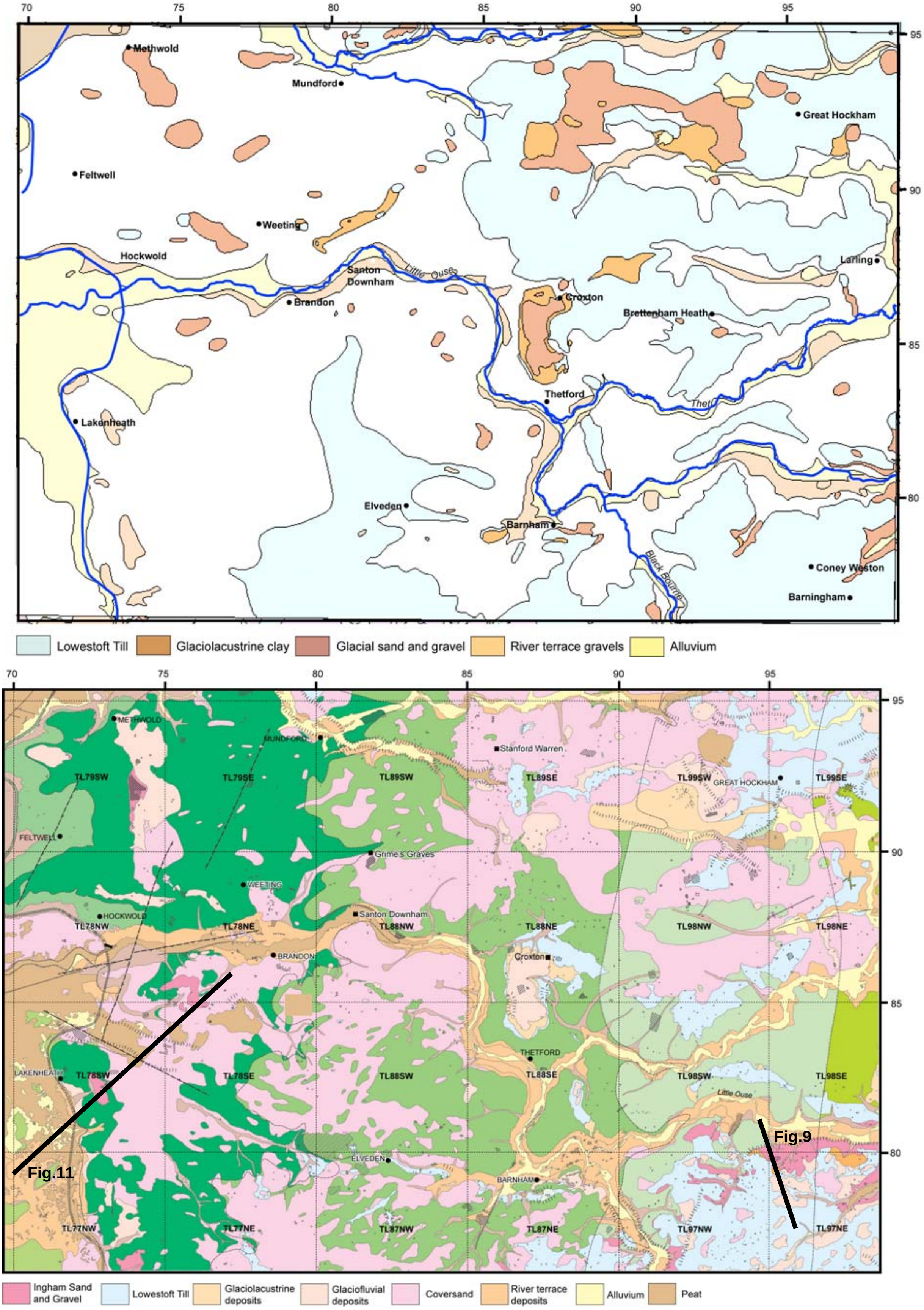

Figure 4. Geological linework from the ‘Old Series’ (top) and ‘Modern’ (bottom) geological maps for the Thetford District. Within the ‘Old Series’ map, bedrock lines have been removed to just show the distribution of superficial deposits. The line of schematic sections Figures 9 and 11 are also shown.

2.2 ADJOINING GEOLOGICAL MAP SHEETS

The new Thetford geological map sheet (Sheet 174) is surrounded by maps of variable age and quality (Table 1; Figure 1). Adjoining map sheets to the northwest (Sheet 159 – Wisbech), west (Sheet 173 - Ely), east (Sheet 175 – Diss) and south (Sheet 188 - Cambridge ; Sheet 189 – Bury St Edmunds; Sheet 190 - Eye) have been resurveyed over the past 40 years to modern geological and cartographic standards. Two adjoining geological maps to the north (Sheet 160 – Swaffham) and northeast (Sheet 161 – Norwich) are generally acknowledged to be of poor quality and in need of resurvey. The Swaffham (Sheet 160) and Fakenham (Sheet 146) geological maps have not been resurveyed since the late nineteenth century but have been re-published as ‘Provisional revisions’ in the 1990s where the ‘Old Series’ geological linework has been fitted to a modern topographic base.

The modern survey of the Thetford District highlighted many problems with the ‘Old Series’ survey, and mapping along the northern margin of Thetford demonstrated that the ‘Old Series’ Swaffham map was surveyed using a similar approach. It is therefore concluded that both the Swaffham and Fakenham maps, together with Norwich, are not presently fit for purpose.

Sheet Number	Sheet Name	Publication of map	Modern Map	Modern SE/SD
129	The Wash	1997	Yes	No
130	Wells	2008	Yes	In press
131	Cromer	2002	Yes	Yes
132	Mundesley	2002	Yes	Yes
145	King’s Lynn	1999	Yes	Yes
146	Fakenham	1999	**No***	No
147	Aylsham	2005	In press	In press
148	North Walsham	2002	Yes	Yes
159	Wisbech	1995	Yes	No
160	Swaffham	1995	**No***	No
161	Norwich	1975	Yes	Yes
162	Great Yarmouth	1994	Yes	Yes
173	Ely	1980	Yes	Yes
174	**Thetford**	**2008**	**2010**	**No**
175	Diss	1993	Yes	Yes
176	Lowestoft	1996	Yes	Yes
188	Cambridge	1981	Yes	Yes
189	Bury St Edmunds	1982	Yes	Yes
190	Eye	1995	Yes	No
191	Saxmundham	1996	Yes	Yes

Table 1. Status of 1:50,000 geological sheets in northern East Anglia. The ‘Modern Map’ category refers to maps surveyed using modern geological and cartographic approaches, with the ‘Modern SE/SD’ referring to the existence of either a modern Sheet Explanation of Sheet Description. * Fakenham and Swaffham are published as ‘Provisional’ maps.

2.3 THE MODERN THETFORD GEOLOGICAL SURVEY

2.3.1 Workflow

The modern geological survey of the Thetford Sheet has many modern techniques and methodologies that were not available to the original survey geologists involved in the 'Old Series' survey of the District. Most notably, these include the use of soil augers, modern cartographic maps and global positioning systems (GPS) for spatial referencing. A feature of the modern Thetford survey and published 1:50,000 scale geological map is that it represents one of the first geological maps to be produced following a new digital workflow system.

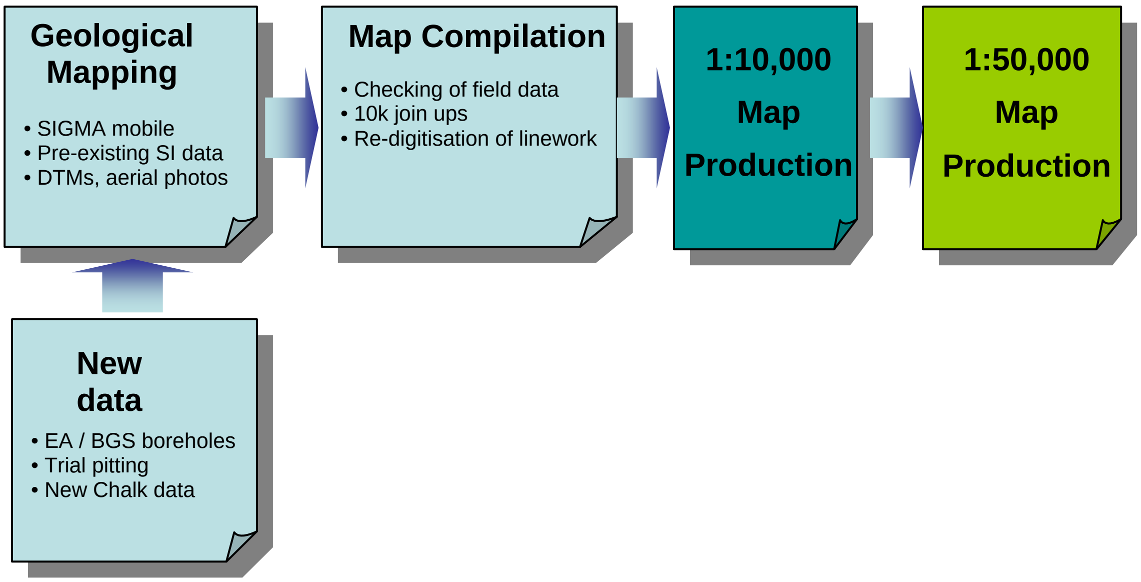

Figure 5. The new digital workflow system for the production employed for producing the Thetford 50k geological map. See also the BGS SIGMA pages for further information.

This new workflow system (Figure 5) involves the capture of field data digitally using the SIGMA Mobile tool – a ruggedised palm-top computer that captures 'live' georeferenced digital data and stores it as a series of databases and GIS layers within the ARC GIS and MS Access software platforms. On completion of the fieldwork, the geological data was re-digitised to produce cartographic quality maps at both 1:10,000 and 1:50,000 scale.

2.3.2 Field survey methodology

Mapping was undertaken over a period of two financial years (2007-2008) following a systematic ground-truthing programme of the Thetford sheet, covering some 575 km^2. The location of geological boundaries and attribution of properties to the geological units were achieved through observations of soil composition, vegetation, shallow augering and geomorphology. This information was supplemented by data derived from aerial photographs, NextMAP digital surface models, old topographic maps, borehole and site investigation records, BGS archives and the scientific literature.

In addition a programme of new site investigations was undertaken with the primary objective to enhance the quality of the survey by gaining a greater understanding of the superficial succession at depth. This programme included trial pits and trenches and medium and shallow-depth boreholes drilled using both percussion and rotary drilling rigs.

3 Nature and form of the bedrock surface

3.1 REGIONAL FORM

The nature and geometry of the rockhead surface within the Thetford District is complex (Figure 6). At a large scale, the rockhead surface is partially controlled by the erosive force of Quaternary ice sheets – both directly and indirectly through the erosion of deeply incised channels by glacial meltwater, and several modern river valleys. At a local scale, periglacial processes and dissolution have created an irregular weathered profile to the upper Chalk bedrock.

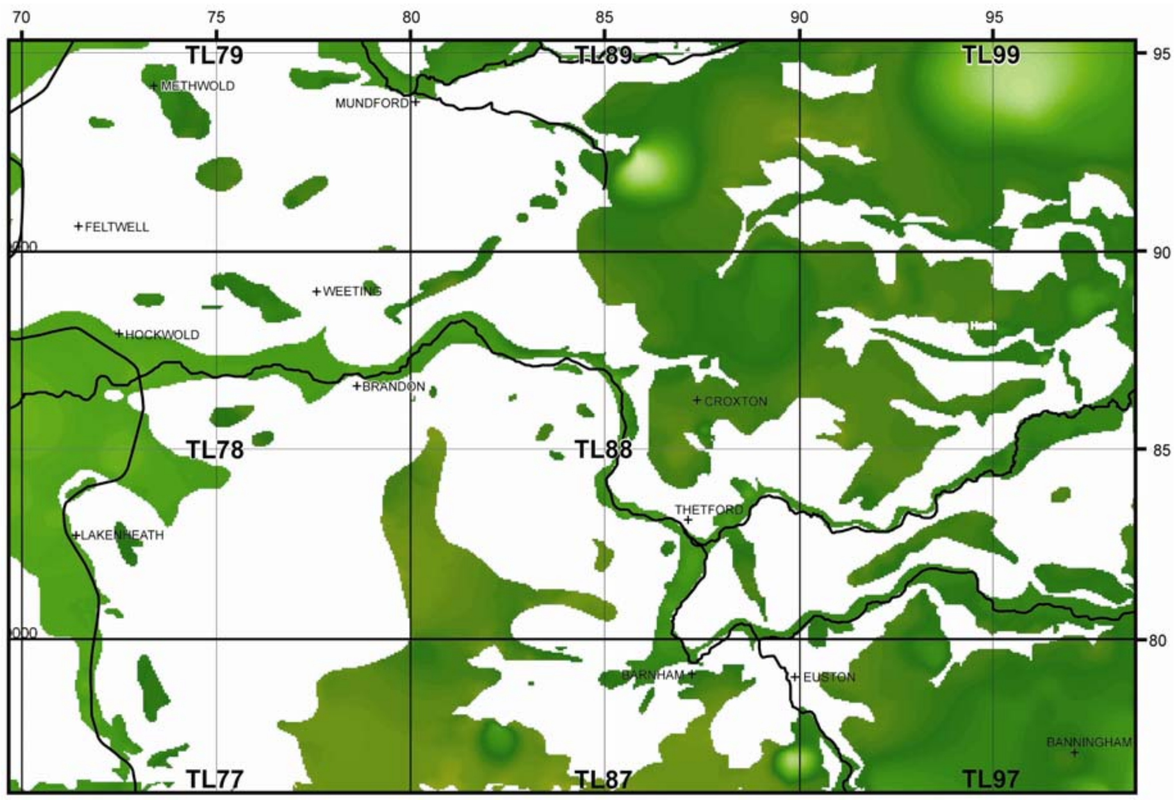

Figure 6. Rockhead model for the Thetford Sheet area based upon boreholes, site investigation data and the presence or absence of superficial units. White areas correspond to outcropping bedrock whereas green areas correspond to areas of thicker drift cover (darker green colours equate to deeper rockhead levels). The linework within this model is unfortunately based upon the 'Old Series' geological linework. However, at a general level the model does demonstrate the occurrence of thicker areas of drift.

3.2 MODERN DRAINAGE

The primary river system of the Thetford District is the Little Ouse. It drains from east to west across the District, and possesses several tributaries including the Black Bourne and the Thet (Figure 2). The precise timing of the creation of the valley of the Little Ouse, plus the Black Bourne and the Thet remains unclear; however, the geometry of the Lowestoft Till Member, which drapes part of the valley flanks, suggests that they may have existed at least in part prior to glaciation during the Middle Pleistocene.

3.3 GLACIAL MODIFICATION AND CONCEALED VALLEYS

The generalised form of the Chalk surface throughout the Thetford District and wider Fen margin is partially a relict of the erosive effects of Quaternary ice sheets. Clayton (2000) modelled the form and patterns of glacial erosion on the Chalk escarpment adjacent to the eastern Fen margin. Clayton concluded that the scarp had been lowered by some 65.7 ms removing a total of 242.9 km^3 of material over an area of 3,696 km^2 within and adjacent to the Thetford District. Chalk material was redistributed as clasts within the Lowestoft Till which is distributed throughout much of central and southern East Anglia, or removed by dissolution.

Several 'concealed valleys' also exist within the Thetford District incised into the Chalk bedrock (Figure 7). They have no obvious surface expression within the modern topography and whilst some examples occur beneath the floodplains of rivers, others are completely unrelated to modern drainage. The existence of 'concealed valleys' – often described as 'tunnel valleys', throughout the East Anglia region was established by Woodland (1942, 1970) based upon water well and borehole records. At a regional scale their spatial distribution is generally understood, although local detail is often lacking - being dependent upon the availability of borehole and site investigation records, terrestrial seismic or airborne electromagnetic data. Woodland argued that the 'tunnel valleys' were created beneath Anglian-age ice sheets by subglacial meltwater under immense hydrostatic pressures. The term 'concealed valley' is used here in preference to 'tunnel valley' – the latter term implies a specific origin and geometric form that is not applicable to all of the 'concealed valleys' within the survey area.

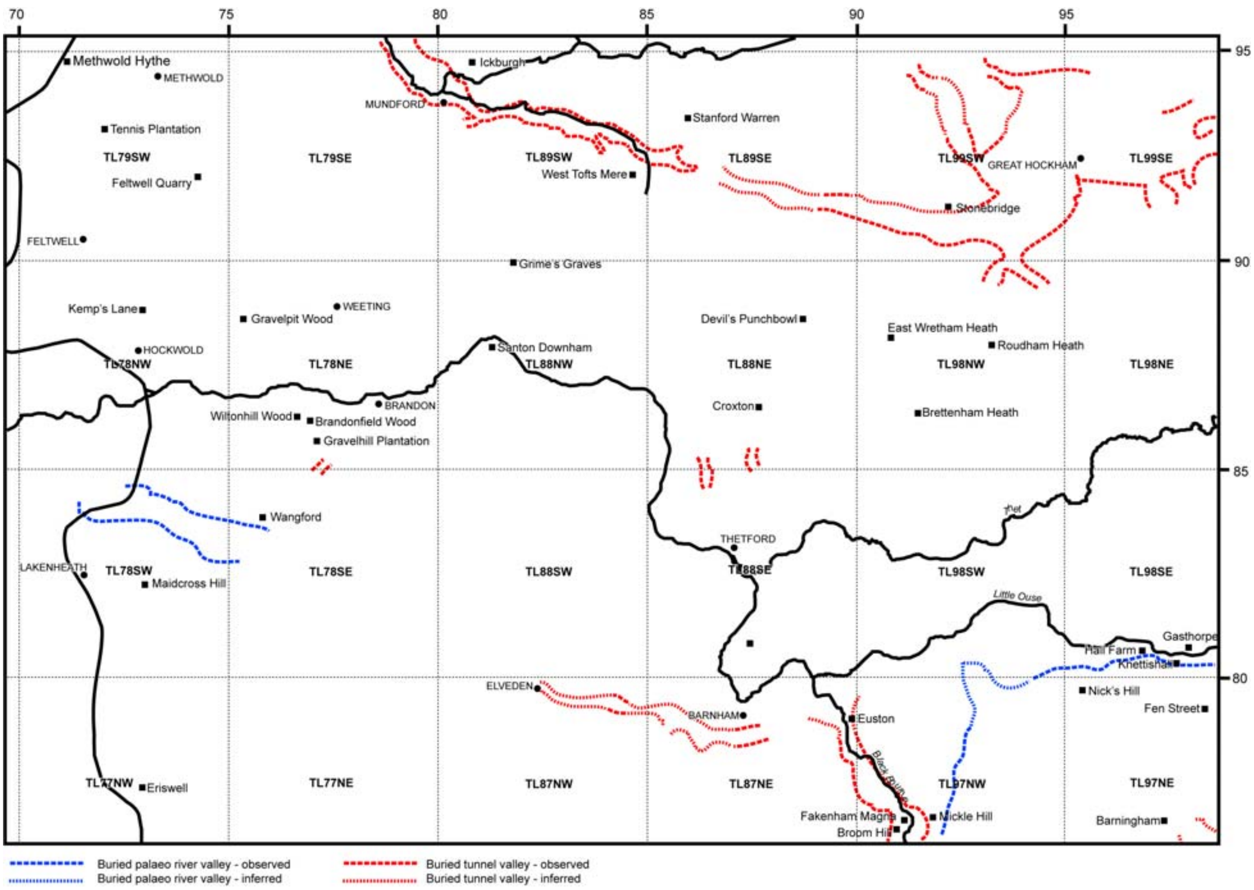

Figure 7. The distribution of 'concealed valleys' within the Thetford District recognised by borehole records.

Three general forms of 'concealed valley' can be recognised including two types of tunnel valley:

- At the largest scale are *buried palaeo river valleys*. This type of valley existed prior to glaciation although their form may have been modified during glaciation as they represent local drainage routes that were probably utilised by glacial meltwater. They are infilled by ancient river sands and gravels that have an increased glacial clastic component towards the top.
- *Linked networks* of *tunnel valleys*. These linked concealed valley systems were either created by, or pre-existing river valleys were over-deepened by, subglacial drainage during glaciation. Typically, these valleys are infilled by a varied mix of sand, gravel and till and may be up to 60 m deep, 100-300 m wide and several kilometres long. One example within the survey area consists of several tributary valleys feeding into a sub-drift basin.
- *Isolated tunnel valleys*. Single tunnel valleys incised into chalk bedrock. These closed valleys can vary in width between 50-100 m, depth between 30-50 m, and length between 200 m and 3 km, and appear to be keel-shaped in long-profile. They are typically infilled by a mixture of sand, gravel and till.

There are two occurrences of buried palaeo river valleys within the Thetford District and both relate to the ancient Bytham River system. The first of these has been traced via borehole records beneath the southern edge of Wangford Fen [TL 751 839]. The buried valley is infilled by Ingham Sand and Gravel, Lowestoft Till and associated glacial outwash and occurs within a much larger area of subdued topography between elevated ground around Lakenheath and to the southwest of Brandon capped by Ingham Sand and Gravel. The significance of this area of subdued topography was commented upon by Lewis (1993) who suggested, based upon the distribution of the Ingham Sand and Gravel that the valley was probably cut by the Bytham River. This hypothesis is supported by this study, but the recognition of the buried palaeo river valley beneath this broader valley identifies a second, previously unidentified episode of fluvial incision. Within the southeastern sector of the District, the northern fringe of the ancient Bytham River Valley can again be determined following the northern boundary of TL97NE, passing southwards across TL97NW past Mickle Hill [TL 918 769] before leaving the Thetford District. Geological mapping and boreholes confirm that the infill of the northern flank of the valley is dominated by Triassic-rich (Bunter quartzite and red mudstone) sand and gravels with occasional lenses of sandy till. Around Barningham in the southeast of the map sheet, boreholes demonstrate rockhead at around 50 m beneath the ground surface. Examination of boreholes further to the south (Sheet 189) and east (Sheet 175) along the southern side of the buried valley also support an over-deepened southern flank of the valley. It implies a polygenetic origin for the buried valley. Firstly, as a pre-glacial river valley – namely, that of the Bytham River. But, secondly, that the Bytham River valley was utilised and over-deepened along the southern valley flank by subglacial drainage forming a 'superimposed' tunnel valley.

One of the largest linked networks of tunnel valleys occurs within TL99SW and TL99SE in the northeast of the survey area around Great Hockham [TL 954 926]. Borehole records revealed that a large basin, up to 40 m deep and 3 km wide and fed by several tributary valleys. It appears to be linked to a major tunnel valley that trends west to east beneath the River Wissey before turning south-eastwards between Mundford [TL 805 945] and Ickburgh [TL 812 949], and extending towards West Tofts Mere [TL 845 919]. This tunnel valley represents an eastwards continuation of a feature first recognised by Gallois *et al*. (1994) beneath the Fens. A second tunnel valley network is recorded by boreholes at Euston and extends southwards beneath the course of the Black Bourne. The northwards extent of this tunnel valley is unknown, but southwards beyond the limits of the Thetford District, it converges with several other tunnel valleys around Honington and Sapiston.

Several smaller, isolated tunnel valleys of limited spatial extent have been recognised within the District including to the south of Brandon [TL 771 851]; west [TL 864 853] and east [TL 880 851] of Thetford; to the south of Barnham [TL 874 785].

4 Superficial Geology of the Thetford District

Within this section the superficial geology of the Thetford District and the mapping rationale that was used in the construction of the new geological map for Sheet 174 is outlined.

4.1 INGHAM SAND AND GRAVEL FORMATION

The Ingham Sand and Gravel Formation consists predominantly of 'Bunter-rich' brown quartzose (vein quartz and quartzite) gravels that were first recognised by Clarke and Auton (1982, 1984) during their Industrial Mineral Assessment Unit (IMAU) survey of central East Anglia. Subsequent research by Rose (1989), Lewis (1993) and Rose *et al*. (1999) has demonstrated that these deposits form part of an extensive spread of sand and gravel that represents the course of an ancient river system called the Bytham River that drained eastern England and the Midlands during the Early and early Middle Pleistocene (c.2.6-0.45 Ma BP). In East Anglia, this river system crossed the chalk escarpment in the vicinity of Mildenhall before flowing eastwards through Bury St Edmunds, Diss, Beccles and crossing the modern coastline between Lowestoft and Great Yarmouth.

Throughout much of East Anglia and the Thetford region there is only minor surface expression of the ancient Bytham River as much of the sediment deposited by the river system is concealed beneath Middle Pleistocene glacial deposits within a large palaeo river valley (Figure 4). Two distinctive lithofacies of Ingham Sand and Gravel have been recorded within the survey area. The first and most widespread facies consist of undifferentiated sands and sands and gravels (Figure 8). Distinctive characteristics are that the gravels are composed mainly of brown quartzose lithologies derived from the 'Bunter Pebble Beds' (Kidderminster Formation) of the West Midlands and the sands typically possess a pinkish to brown hue. Smaller proportions of red sandstone, mudstone and locally derived flint may also be present as clasts within the gravels. These sediments represent fluvial sedimentation on an active river braid-plain. The second lithofacies has only been recognised at depth within boreholes and its geometric relationship to other Bytham river deposits is shown in Figure 9. It consists of a series of reddish-brown silts and clays that passes upwards into grey silts and clay with occasional pebbles of chalk and flint. A preliminary examination of heavy minerals taken from borehole samples shows that this facies change is also characterised by a switch in heavy mineral composition from samples dominated by resistant Mesozoic species (e.g. rutile, zircon, staurolite and kyanite) to samples dominated by far-travelled species (e.g. amphiboles, epidotes and to a lesser extent pyroxene). It is considered that these lithological changes reflect the development of a glaciolacustrine basin within the Bytham River valley and the progressive enrichment of the Bytham sediments with glacially-derived materials from the Anglian-age British Ice Sheet. The elevation of these deposits, at approximately 28 – 31 m, is some 20 m higher than the surface of the terrace that aggraded immediately prior to the Anglian glaciation. It demonstrates that the basin must have extensive in size and was dammed downstream.

Geological mapping reveals two concentrations of Ingham Sand and Gravel. Firstly, within the western part of the sheet area between Feltwell and Lakenheath, sands and gravels occupy hollows or planar bench features cut into the chalk surface and form small patches, hillocks or valley-side outcrops of gravel. Secondly, within the south-eastern sector of the sheet, borehole records and mapped outcrops show that sands and gravels occupy a major concealed valley south of a line linking Fakenham Magna, Riddlesworth and Gasthorpe. Several boreholes drilled as part of the geological survey in the vicinity of Sapistan and Barningham failed to reach rockhead before terminating at approximately 20 m, revealed a complex sequence of sand and gravel with beds of laminated silt and clay buried beneath Lowestoft Formation till.

LITHOSTRATIGRAPHY	LITHOLOGY	MODE OF DEPOSITION	AGE
Lacustrine deposits	Laminated silt, clay and peat	Infill of pingos and palsas	Holocene
Alluvium	Silty, clayey sand	Fluvial, floodplain	Late Pleistocene to Holocene
Peat (undifferentiated)	Peaty clay and sand	Various	
River terrace deposits	Sand and gravel, sand	Fluvial, braided channel	
Coversand	Sand sheets, dunes	Aeolian	
Elvedon Formation			
Barnham Silt and Clay Member	Laminated silts and clays	Lacustrine, fluvial overbank	Middle Pleistocene Hoxnian Interglacial
Lowestoft Glacigenic Formation			Middle Pleistocene Anglian Glaciation
Croxton Sand and Gravel Member	Flint and chalk-rich sand and gravel	Glaciofluvial outwash	
Lodge Farm Silt and Clay Member	Laminated silts and clays	Glaciolacustrine	
Lowestoft Till Member	Clay-rich, chalky diamicton	Subglacial till	
Happisburgh Glacigenic Formation			Middle Pleistocene Happisburgh Glaciation
Coney Weston Sand and Gravel Member	Quartzose and flint-rich sands and gravels with chalk and erratics	Glaciofluvial outwash	
Starston Till Member	Sandy-clay diamicton	Subglacial till	
Ingham Sand and Gravel Formation			Early to early Middle Pleistocene
High Lodge Silt Member	Organic-rich stratified silts	Fluvial, over-bank	
Ingham Sand and Gravel Member	Quartzose-rich sands and gravels	Fluvial, braided channel	

Table 2. Lithostratigraphy of superficial deposits within the Thetford District.

Around Feltwell in the northwestern corner of the Thetford Sheet, ISAG crop-out at two different elevations. Firstly, between the north of the village and Little Oulsham Drove, several small patches [TL 705 917; TL 709 915; TL 709 910] of Bunter pebble-rich gravel were recorded at approximately 9 m OD. Augering revealed these patches to occupy shallow hollows in the chalk surface. Secondly, to the east of Feltwell near Methwold Warren, a working pit [TL 741922] shows up to 3 m of cross- and horizontal-bedded Bunter pebble-rich sand and gravel with abundant white flints overlain by 2 m of flint-rich glacial outwash assigned to the Croxton Sand and Gravel Member. Palaeocurrent measurements within the ISAG indicate a direction of drainage towards the south and southwest. The base of the ISAG adjacent to the quarry is indicated by a concave slope break that occurs between 22-25 m and a marked change from chalky to Bunter pebble-rich soil: it can be traced northwards and southwards until truncated by glacial outwash.

Figure 8. Sand and gravel facies of the Ingham Sand and Gravel Formation exposed in a fresh face at Feltwell Quarry [741,922]. Overlying the sands and gravels is the chalky Lowestoft Till Member and several generations of rubified palaeosol and coversand. Note the deep solution structures within the till, and the periglacial involutions just beneath the ground surface. Height of section 4 ms; facing east.

To the southwest of Weeting, a small outcrop of Bunter pebble-rich gravels occurs between 5 - 8 m [TL 764 677] on the northern valley side of the Little Ouse where they appear to be cut into the Chalk. On the southern side of the Little Ouse, Bunter pebble-rich gravels of Ingham Sand and Gravel form caps to several adjoining chalk hillocks to the west of Brandon. These include Wiltonhill Wood [TL 751 857], Brandonfield Wood [TL 759 859] and Gravelhill Plantation [TL 761 851]. The base of the ISAG at these hillocks occurs between 28 - 29 m and is marked by a discontinuous concave slope break. Gravelhill Plantation has previously been reported by Flower (1869) and Wymer (1985) who described the palaeolithic archaeology of the site.

Ingham Sand and Gravel also outcrops on the western side of the Chalk escarpment at Maidscross Hill [TL 726 826], situated to the west of Lakenheath, where the gravels have been extensively quarried. On the western, southern and northern edges of the outcrop, where a maximum thickness of 7 m can be inferred from elevation data, the base of the Ingham Sand and Gravel rests directly on Chalk at between 25 - 26 m but cuts down on the eastern side of the hill to 12 m. Several small sections were excavated by hand, and a total of 12 palaeocurrent measurements taken – they indicated a local palaeo-flow direction towards the south-southwest and south-southeast.

Lithological examination of the clast component of the Ingham Sand and Gravel at Maidcross Hill has identified that a significant proportion (24%) of the clast assemblage is composed of Chalk. Whilst half of the Chalk is derived locally and is of the same Chalk lithology as has been mapped in the vicinity of Lakenheath, up to half of the Chalk population consists of much younger (i.e. stratigraphically higher) Chalk types – particularly the Lewes Nodular Chalk (D. Aldiss, personal communication, 2008). Within the Thetford District, the base of the Lewes Nodular Chalk crops-out approximately 10 km to the east of Lakenheath near Santon Downham. It implies that an east-bank tributary of the Bytham River fed easterly-derived materials into the river to the north of Lakenheath. It is a strong possibility that this tributary may have occupied the valley of the modern Little Ouse, as the geometry of the Lowestoft Till relative to the river valley suggests that a major valley existed here prior to the Anglian Glaciation.

4.2 HAPPISBURGH GLACIGENIC FORMATION

The Happisburgh Glacigenic Formation is the basal suite of glacial deposits in East Anglia and was deposited by an advance of British Ice (Lee *et al*., 2002) into northern East Anglia approximately 600 ka BP (Lee *et al*., 2004) – the so-called 'Happisburgh Glaciation'. The deposits are equivalent to the First Cromer Till of northeast Norfolk (Banham, 1968) and the Norwich Brickearth observed to the east within the lower Waveney Valley and coastal sections to the north of Lowestoft (Hopson and Bridge, 1987; Arthurton *et al*., 1994).

4.2.1 Starston Till Member

The Starston Till Member is a brown, matrix-supported diamicton that has a sandy-silt or sand-clay matrix with sporadic clasts of flint, quartzose material and red mudstone and sandstone. It is generally massive but can exhibit a weakly-stratified appearance with lenses and stringers of sorted sand. It is highly compact and contains numerous vertical and horizontal fractures.

The present survey and borehole records show that the deposit is sparse within the Thetford District, being preserved only within a deep buried former river valley cut into the Chalk surface in the southern and south-eastern sectors of the District (Figure 9).

A 0.4 m thick horizon of Starston Till was recorded in disused brick and gravel workings near Fakenham Magna [TL 906 759] where it rests upon Ingham Sand and Gravel. The diamicton can be traced northwards for 200 m adjacent to the 39 - 40 m contour before it pinches-out between Ingham Sand and Gravel and Lowestoft Till in the vicinity of Broom Hill.

To the south of Barningham [TL 971,765], 1.2 m of Starston Till was recorded within BGS borehole TL97NE 50 between 24.0 - 24.8 m. Within this borehole, the till overlies Ingham Sand and Gravel and is in turn overlain by the Coney Weston Sand and Gravel Member and the Lowestoft Till Member.

At Nick's Hill [TL 951 798) to the southeast of Knettishall, Lewis *et al*. (1998) recorded up to 1 m of Starston Till within a disused pit, where the till occupies a shallow channel cut into Chalk bedrock and is inter-bedded with the Coney Weston Sand and Gravel Member. To the northeast of this locality, a small outcrop of Starston Till occurs adjacent Hall Farm [TL 965 804] Knettishall, where till has previously been dug from a series of small pits for brick making. The nature of the outcrop here suggests that it occupies a shallow channel, in a similar manner to the Starston Till at Nick's Hill but cut into Ingham Sand and Gravel.

4.2.2 Coney Weston Sand and Gravel Member

The Coney Weston Sand and Gravel Member is a coarse-grained, outwash facies of the Happisburgh Formation that typically occurs either above, or inter-digitated with, the Starston Till (Lewis *et al*., 1998). The sands and gravels were deposited as part of a proglacial outwash drainage system that corresponds to the retreat of the same ice sheet that deposited the Starston Till. The deposit consists of flint-rich gravels with smaller proportions of quartzite, vein quartz, chalk and sporadic igneous and metamorphic erratics. It can be distinguished from Ingham Sand and Gravel by its higher flint content and from Croxton Sand and Gravel by its lower chalk and black flint content.

The stratotype locality for the Coney Weston Sand and Gravel is Nick's Hill [TL 951 798] near Knettishall, where the gravels were first observed by Lewis and Rose (1991) and Lewis *et al*. (1991). Although Nick's Hill pit was not accessible during the present survey, sand and gravel was mapped adjacent to the pit and eastwards towards Fen Street [TL 985 794] beneath the now-disused Knettishall airfield. The irregular base of the Coney Weston Sand and Gravel, which ranges in elevation between 29 and 33 m, implies substantial degradation of the upper surface of the ISAG occurred prior to glaciation. 6.5 m of Coney Weston Sand and Gravel were also recorded between the Starston Till and Lowestoft Till in borehole TL97NE 50 to the southeast of Banningham [TL 971 764].

4.3 LOWESTOFT GLACIGENIC FORMATION

4.3.1 Lowestoft Till Member

The Lowestoft Till Member is the most extensive till unit in the Thetford District. It was deposited by the British Ice Sheet during the Anglian Glaciation of the Middle Pleistocene some 450 ka BP. Two different facies of Lowestoft Till have been recognised: (1) a dark yellowish brown, matrix-supported diamicton with a sandy-clay matrix texture and abundant flint and chalk clasts; (2) a dark grey to light grey, matrix-supported diamicton with a clay-rich matrix texture and abundant flint and chalk clasts. Lithological and structural differences between these tills have previously been thought to relate to different ice advances during the Anglian (Baden-Powell, 1948; West and Donner, 1956). Firstly, an ice advance from the Fen Basin to the west that deposited grey, clay-rich till ('Jurassic Boulder Clay' or 'Lowestoft Till *s.s.*') composed largely of Kimmeridge Clay derived material; and secondly, a later advance from the north that flowed southwards along the strike of the Chalk outcrop depositing a more sandy and chalk-rich till ('Chalky Boulder Clay' or 'Gipping Till'). For this survey of the Thetford District, the palynology of these till facies was investigated by Riding (2008) to test this former work. Both till facies proved to consist mainly of Kimmeridge Clay, implying that lithological and structural variations between these till facies do not relate to different ice advance but, instead, are simply a function of differential incorporation of bedrock lithologies during a single glacier advance from the west.

Overall, the extent of the Lowestoft Till within the Thetford District is considered to be far less than previously shown on the 'Old Series' map. The examination of derived palynomorphs from localities previously considered to be Lowestoft Till indicates that much of the Lowestoft Till on the 'Old Series' map is in reality, weathered Chalk (Riding, 2008). The Lowestoft Till within the Thetford District typically occurs as either: (1) thin localised ribbons that follow depressions within the chalk surface (e.g. concealed 'tunnel' valleys); or (2), extensive spreads that form the upper infill of large concealed basins or former river valleys (Figures 4 and 9). In both cases, Lowestoft Till generally only occurs within topographic lows, the exception being around Thetford itself, where till is draped around a pre-existing Chalk-high. The limited spatial distribution of till suggests that the Thetford District was an area of net-erosion during the Anglian Glaciation (Clayton, 2000).

The most extensive spreads of Lowestoft Till occur through the southern and southeastern parts of the Thetford District within quarter sheets TL87NE, TL97NW and TL97NE. These spreads underlie a gently-undulating plateau on the southern side of the Little Ouse that extends eastwards from Honnington Airfield towards Barningham and Knettishall. Between Fakenham Magna and Euston, the plateau is dissected by the Black Bourne that drains northwards into the Little Ouse. The till plateau is typically in the region of 5-12 m thick with Lowestoft Till resting either upon Chalk bedrock or, more commonly, sand and gravel / till of the Ingham Sand and Gravel or Happisburgh formations. To the south of Barningham, boreholes TL97NE 2, 3 and 12 proved a concealed valley cut into the Chalk, the base of which descends in places to at least -10 m. This valley is filled by up to 55 m of Lowestoft Till and outwash sand and gravel which suggests that its formation and the deposition of the till were broadly contemporaneous.

To the north of the Little Ouse, there are several patches of Lowestoft Till on valley sides around Riddlesworth, Brettenham and Thetford. Here, till underlies part of the high ground (up to 54 m) between the northern fringes of Thetford [TL 868 838] and Croxton [TL 873 874] where it tends to form heavy and chalky clay soils. Lowestoft Till is exposed in several small, disused pits just north of the Thetford Bypass. Within these pits [TL 862 858; TL 862 860] up to 1.2 m of brown, clayey diamicton with chalk pebbles can be observed. Much of the Lowestoft Till is this area is buried beneath Lowestoft Formation glaciolacustrine deposits and outwash sands and gravels but mapping and borehole data show that in places it may be up to 10 m thick. The geometry of the till relative to the underlying Chalk implies that the ice sheet effectively 'smeared' the till over a pre-existing Chalk hill.

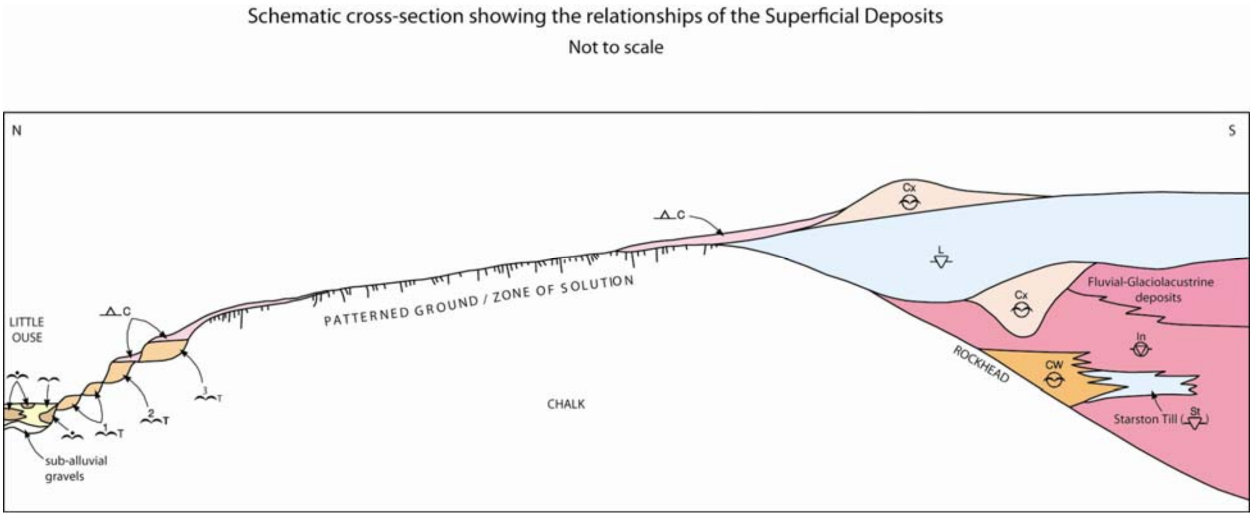

Figure 9. Generalised schematic section showing the geometry of the Lowestoft Till Member (blue, prefix L) across the southern and central parts of the Thetford survey area.

4.3.2 Lodge Farm Silt and Clay Member

The Lodge Farm Silt and Clay Member outcrops within the northern Thetford [TL 868 838] and Croxton [TL 873 874] area where it overlies the Lowestoft Till north of the A11

Thetford by-pass. It forms more silty and less stony soils than the Lowestoft Till and to the south, within the urban area of Thetford, it is recorded in boreholes and site investigation reports. The deposit is up to 4 m thick and consists of beds of stiff, blue-grey clay and brown silt with sporadic thin seams of sand, that were laid down within a glaciolacustrine basin during the retreat of ice from the Thetford area during the Anglian Glaciation. The Lodge Farm Silt and Clay rests irregularly upon the upper surface of the Lowestoft Till suggesting that prior to its deposition the upper surface of the till was partially scoured. An interesting feature of this inferred glaciolacustrine basin is that it underlies high ground in the present day landscape. This can be explained in two possible ways: (1) that the surface of the surrounding topography has been lowered since the Anglian Glaciation by subaerial processes; (2) that the glaciolacustrine basin was dammed either ice and / or moraine dammed. The first scenario would require up to 25 m of material to have been eroded across much of the Thetford region following deglaciation. Whilst this theory is plausible, there is no lithological evidence within any of the terraces of the Little Ouse to support such an occurrence. It is suggested tentatively, that scenario 2 may be the most likely.

4.3.3 Croxton Sand and Gravel Member

The Croxton Sand and Gravel Member is a coarse glaciofluvial outwash sand and gravel that was laid down during the retreat of the Anglian ice sheet. It consists of a coarse sand and gravel of variable thickness that contains abundant proportions of brown, white and black flints, with scattered clasts of Bunter quartzite, vein quartz, chalk and crystalline materials. The deposit outcrops extensively across the whole survey area. Within the western part of the District, the deposit crops-out in patches along the Fen margin including Tennis Plantation [TL 718 933] near Methwold Hythe, and along the Chalk scarp between Methwold and Weeting. At Feltwell Quarry [TL 741 922] and the surrounding area, the deposits infill a broad incision cutting down through the Ingham Sand and Gravel and Lowestoft Till. Further to the south near Hockwold, the gravel forms a ridge that extends westwards for approximately 2.5 km from Gravelpit Wood [TL 751 885] to the northern end of Kemp’s Lane [TL 727 889]. Survey observations and exposures at a series of disused pits at Gravelpit Wood suggest that the ridge is composed of clast-supported cobble gravel. This, combined with the symmetrical form of the ridge and its relatively steep sides is consistent with the morphology and sedimentology of an esker. Unfortunately, it was not possible during the survey to investigate the base of this landform and confirm this interpretation - often, the substrate beneath eskers has been eroded by subglacial meltwater forming Nye Channels. Further to the east near Stonebridge [TL 926 922] the sands and gravels appear to form part of a large fan dipping eastwards into a large concealed basin. The true spatial extent of this fan is not known because it is in-part concealed by coversand.

The significance of these gravels is intriguing. Gibbard *et al*. (2009) suggests a more limited spatial extent to these gravels and argues that they form part of a glacial outwash complex associated with the occupation of the Fen Basin by an ice sheet during a post-Anglian glaciation. According to Gibbard *et al*. drainage from this ice sheet was directed eastwards along the valleys of the Little Ouse and Waveney and out into the North Sea Basin. Evidence collected as part of this survey disagrees with such a model. Firstly, evidence for this outwash (which takes the form of the Croxton Sand and Gravel) is far more extensive than argued by Gibbard *et al*. and extends across the whole of the Thetford survey area at all elevations. Secondly, the sands and gravels at several localities are inter-bedded with the Lowestoft Till implying that the two deposits are contemporaneous. We argue, that that the Croxton Sand and Gravel was deposited during a widespread retreat of the Anglian ice margin northwestwards across the Thetford survey area.

4.4 ELVEDEN FORMATION

4.4.1 Barnham Silt and Clay Member

The Barnham Silt and Clay Member is part of the Elveden Formation. It occurs discontinuously at outcrop and in boreholes between Barnham [TL 873 789] and Elveden [TL 810 804] where it forms part of the fill of a small concealed valley. The origin of this valley is unclear as it is much shallower than the tunnel valleys that have been observed elsewhere within the region. However, the fact that the basal infill of this valley is Lowestoft Till Member, suggests that the valley was in existence during the Anglian Glaciation. The deposit consists of organic silt and clay that contain a temperate flora and fauna characteristic of a slow moving stream or river (Ashton *et al*., 1994, 2005). Of particular note is that the deposit contains relatively abundant archaeological evidence in the form of stone tools and butchered bones suggesting that Palaeolithic humans colonised this ancient valley. Age determinations based on biostratigraphy and Amino Acid Racemization (AAR) demonstrates that the deposit can be assigned to the Hoxnian Interglacial (Ashton *et al*., 2005).

4.5 FLUVIAL DEPOSITS OF THE LITTLE OUSE AND TRIBUTARIES

4.5.1 River Terrace Deposits

The Thetford District is drained largely by the Little Ouse and its catchment. The river flows westwards from its source at Redgrave near Diss, through Thetford and Brandon and into the Great Ouse at Brandon Creek (West, 2007). Three separate river terrace aggradations have been mapped discontinuously across the Thetford region and on the geological map these are labelled Terraces 1 to 3 (Figure 10). Each terrace aggradation represents different stages of sediment accretion and river braid-plain activity associated with cold-climate processes in the Little Ouse catchment. Subsequent long-term neotectonic uplift and changes in fluvial regime (in response to climatic amelioration), have caused the Little Ouse to down-cut and incise through the previous aggradation and establish a lower valley base.

Individual aggradations may be up to 4 m thick and consist of sand and flint-rich gravelly sand with clasts ranging in size from cobble to gravel grade. Terrace 3 is the highest and oldest aggradation and is only partially preserved between Santon Downham and Rushford where its surface lies approximately 10 m above the level of the modern floodplain. Terrace 2 can be traced upstream from Santon Downham and lies about 6 m above the modern floodplain. In the vicinity of Barnham and Euston deposits assigned to Terrace 2 appear to pass laterally into some of the older coversand horizons. Terrace 1 can be traced discontinuously along the length of the entire catchment and can be sub-divided into a number of separate terrace facets. The highest terrace facet within Terrace 1, commonly passes laterally into coversand. East of the Fen edge, these terrace facets are discontinuous in nature and for the purposes of simplifying the geological map at 1:50,000 scale have been merged together. West of the Fen margin, it has been possible to delineate three separate terrace facets based upon elevation adjacent to the Little Ouse between Eriswell, along the southern boundary of the District, and Hockwold where they locally form ‘islands’ surrounded by Fen peat. Examination of borehole and site investigation records within the eastern part of the Fen Basin, have shown that Terrace 1 gravels extend westwards some 10 km beyond the western margin of the Thetford sheet before pinching out (Figure 11).

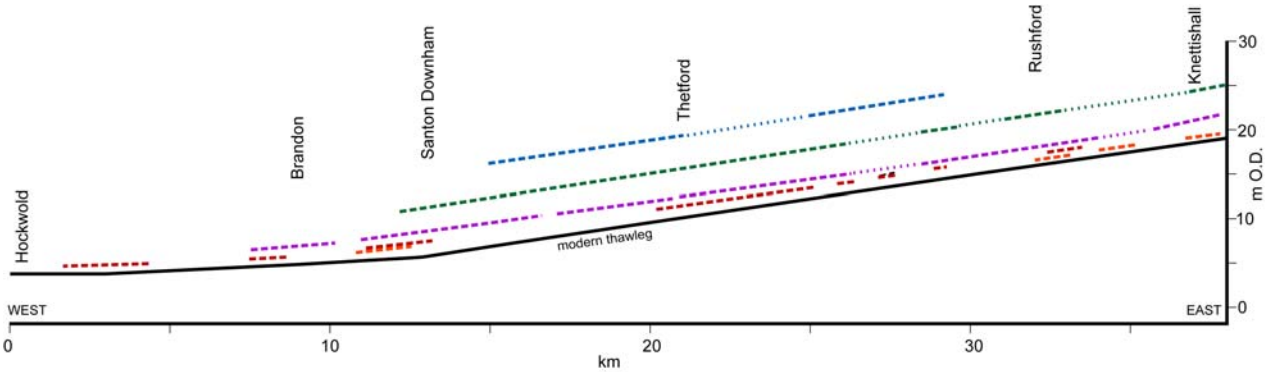

Figure 10. Long profile terrace geometry of the Little Ouse. The blue line corresponds to the surface of Terrace 1; the green line – Terrace 2; and the purple, red and orange lines – Terrace 1 and associated facets.

River terraces have also been recognised along two of the tributaries of the Little Ouse including the Black Bourne and the River Thet. From their elevations, these terraces appear to be equivalent to Terrace 1 (and associated facets) of the Little Ouse.

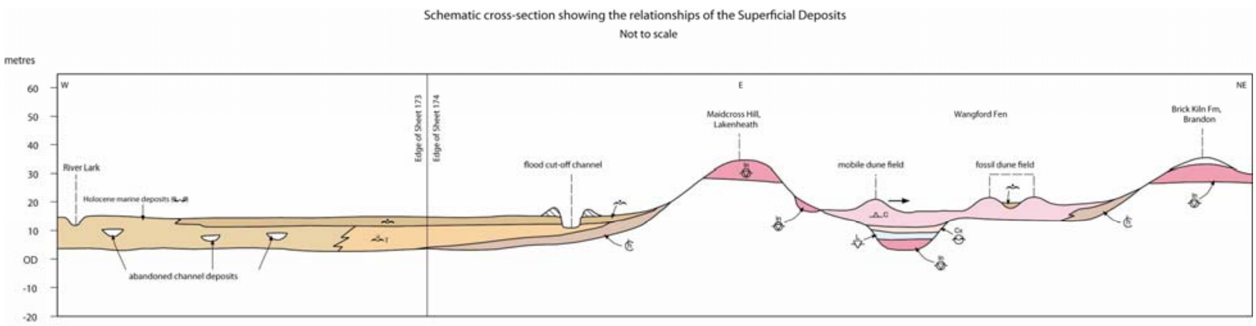

Figure 11. Generalised schematic model of the eastern Fen margin within the Thetford survey area, showing the westwards extension of the lowest terrace aggradation of the Little Ouse into the Fen Basin.

4.5.2 Alluvium and Peat

The floodplains of the Little Ouse and its tributaries within the Thetford survey area are underlain by extensive tracts of alluvium and peat. Morphologically, the floodplains are flat and their margins are delineated by a laterally-continuous concave break of slope that forms the base of the valley flanks. The alluvium is variable in composition but generally consists of a brown to grey sandy silt with sporadic flint pebbles and inter-bedded peat. It becomes more peaty in the lower reaches of the Little Ouse.

4.5.3 Valley Head

Valley head forms a slope wash that has moved downslope under the influence of gravity. Within the Thetford survey area, the head is confined to tributary valleys where the slope wash has effectively been channelled – hence the term 'valley head'. Head appears to be less widespread than for example, in northern East Anglia, where it is a common deposit and is often inter-stratified with the modern alluvium. By contrast, within the Thetford area 'valley head' typically inter-digitates with either Terrace 2, or higher facets within Terrace 1. This suggests that since the last phases of valley head deposition, river base-levels have lowered on at least one separate occasion and there has been minimal slope wash since.

4.6 PERIGLACIAL PHENOMENA

The Thetford area forms part of the Brecks which extends across much of southern Norfolk and northern Suffolk. The Brecks possesses a unique geology, flora and fauna which owe much of their existence to its periglacial legacy (Figure 10). Whilst there is abundant evidence of this periglacial activity during the Late Pleistocene and Early Holocene (c.0.11 Ma – 8 ka BP), there is subtle evidence that suggests that similar periglacial processes have acted upon the landscape of the Thetford region throughout the Pleistocene. Within this section, the periglacial legacy of the Thetford report area is outlined focussing on the localised weathering of the Chalk surface, the development and distribution of patterned ground, coversand and palsas.

4.6.1 Chalk Weathering

Whilst the large-scale morphology of the Chalk surface has been generated by the development of modern and ancient drainage and by the action of Pleistocene ice sheets and subglacial drainage, the localised form of the Chalk surface has been strongly modified by dissolution and periglacial weathering. Auger holes, borehole records and trial pits reveal that the top surface of the Chalk is highly irregular and variable in nature due to intensive weathering. Despite over 6,000 data points it has proved impossible to produce a high-resolution (e.g. m-scale) model for the Chalk surface due its variable form, and in general, it should be assumed that the irregular chalk surface extends across the entire survey area unless site specific data reveal local anomalies.

A series of five shallow boreholes was drilled in the vicinity of Wiltonhill Wood [TL 751 859] near Brandon to determine whether spatial and / or geological controls could be identified as controlling factors in chalk weathering. Examination of the cores revealed the following:

- Where Chalk bedrock crops-out at the surface, it typically may be weathered into broken-up ‘blocky Chalk’, or totally de-structured and have a ‘putty-like’ consistency. The depth of this weathered zone can vary between 0 and (rarely) 5 m.
- The development of intense zones of Chalk weathering may possibly correspond to zones of more porous / higher permeability chalks. Experimental work undertaken by Jerwood *et al*. (1990) shows that repeated freezing of pore-water (i.e. freeze-thaw) and the intergranular growth of salt crystals breaks down Chalk. This would be much enhanced in highly porous or permeable Chalk strata. Further work involving sediment peels taken from borehole cores is being undertaken by the authors.
- Small-scale solution features are very common in the Chalk – especially where it has been buried beneath coversand, river terrace deposits and glacial sands and gravels. Such solution features are highly variable in distribution and scale ranging from 0.2 m-8.0 m in depth and 0.2-1.4 m diameter. Solution features should therefore be expected in all areas of Chalk outcrop and near-surface sub-crop.

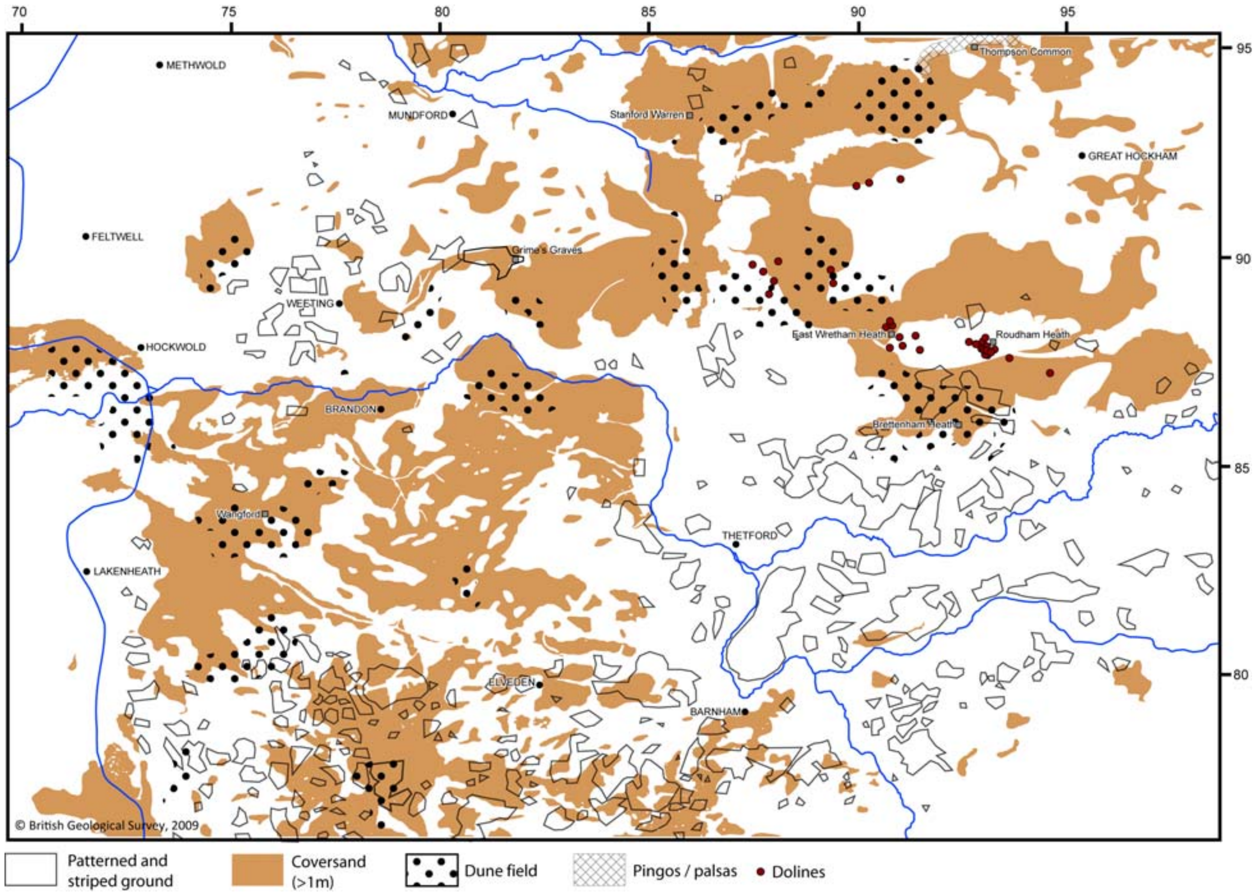

Figure 12. Distribution of periglacial phenomena in the Thetford District including patterned and striped ground, coversand, dune fields, pingos, palsas and dolines. The extent of patterned and striped ground is based on previous mapping during the 1960s by Frank Nicholson (unpublished data) and the recent geological survey.

4.6.2 Large-scale solution features - dolines

Dolines are natural enclosed depressions commonly associated with carbonate dissolution within areas of carbonate bedrock. Various types of doline have been recognised depending on whether the dominant mode of formation is controlled by dissolution, collapse or suffusion and subsidence.

The Devil's Punchbowl [TL 878 892] situated to the north of Croxton is the most famous and accessible example in the Thetford District. However, other possible dolines have been recognised just north of the Devil's Punchbowl within the Ministry of Defence Training area and to the east adjacent to East Wretham Heath [TL 910 880] and Roudham Heath [TL 928 877] (Figure 12). An apparently linear cluster of dolines is broadly aligned along a west-northwest – east-southeast axis between Croxton and Roudham Heath. The cause of this alignment is not understood; however, it is possible that it could relate to a zone of faulting or jointing within the Chalk. The origin of dolines within the Thetford District has not been studied but extensive evidence for Chalk dissolution throughout the region suggests that dissolution may be the dominant driving mechanism.

4.6.3 Patterned Ground

A particularly distinctive feature of the Breckland landscape is the phenomenon of 'patterned ground' – know locally as the 'Breckland Stripes' (Figure 12). They are produced by periglacial processes such as frost heave and freeze-thaw which act to remobilise and sort different clastic materials (Washburn, 1970). They are a very common feature of modern periglacial landscapes. Patterned ground can often by recognised by examining localised changes in vegetation and its distribution can therefore be mapped from aerial photographs (Figure 13). Unfortunately, visibility of such features is often highly dependent on the time of year during which the aerial photographs were taken. Furthermore, modern agricultural practices such as ploughing and de-stoning often destroy the surface expression of these features.

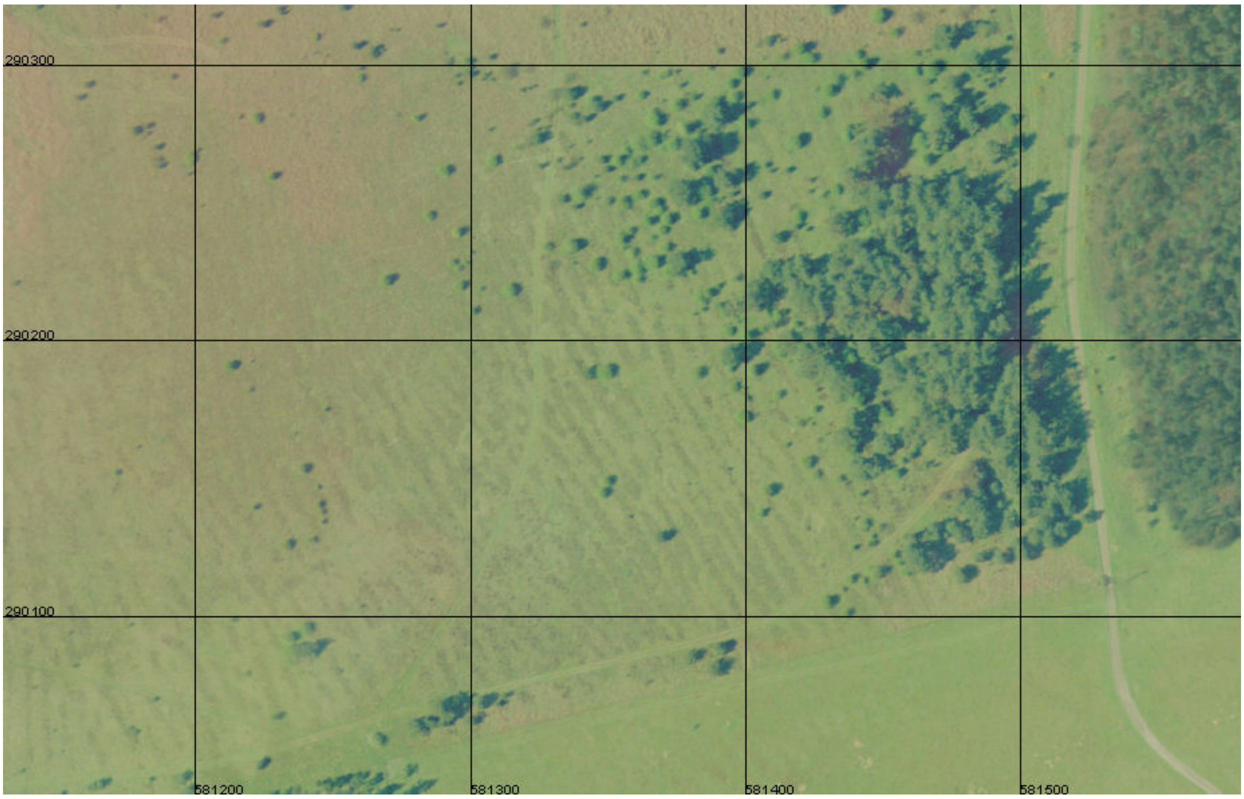

Figure 13. Aerial photograph showing 'patterned ground' near to Grimes Graves [TL 814 901].

Figure 14. A series of linked photographs showing a trial pit through an area of patterned ground at East Farm, Barnham [TL 878 786]. The excavation revealed deep solution features developed within the chalk, plus a high degree of mixing between the top weathered zone within the Chalk and overlying coversand layers. Photo: Stephen Hitchens.

Within the Thetford area, patterned ground has a wide distribution but is most commonly preserved in areas where glacial deposits are absent, especially to the east of Thetford, between Lakenheath and Barnham, and around Weeting. Trial-pitting has been undertaken as part of this geological survey at Brettenham Heath [TL 922 864] and Barnham [TL 878 786] to determine the character and nature of patterned ground (Figure 14). Investigations reveal a close relationship between the periglacial processes that produced the patterned ground, and Chalk dissolution that has affected the upper horizons of the Chalk bedrock. Many of the structures – including involuted structures, flame structures and disharmonic folding, suggest that deformation and mixing occurred within a fluidised active layer.

4.6.4 Coversand

Coversand is used within the context of this geological survey in a descriptive rather than genetic sense and refers to the veneer of sand that blankets much of the Thetford District. On the geological map, coversand is shown only where it exceeds a thickness of 1 m and its distribution has been established on the basis of detailed soil auger information (Figure 12). Research has demonstrated that the principal origin of the coversand is as a windblown deposit which has been locally remobilised by periglacial and fluvial activity.

Across the survey area, it has been possible to identify several different geomorphological and geometric sub-divisions of the coversand. However, it has not been possible to systematically map each of the sub-divisions because in places their form has been masked and degraded by modern agricultural and forestry practices.

- *Sand sheets*: planar bodies of sand that have no obvious surface form. Excavations reveal that these sand sheets can range in thickness from 0.4 to 2 m in thickness and typically contain scattered angular white flint clasts, some of which show wind polishing (e.g. ventifacts and dreikanter), and diffuse layers of peat.
- *Dune fields*: dunes can take various morphological forms and these range from a classic egg-box type topography composed of multiple dunes, to long linear sand ridges, and finally to isolated forms. Their preservation is best observed in places such as Wangford Fen [TL 757 841] and Brettenham Heath [TL 922 864].

In many parts of the survey area, zones of extensive coversand are now intensively managed to prevent soil deflation and sand remobilisation. Soil deflation and sand remobilisation have, from the Middle Ages to recent times, been major problems encountered throughout the Brecks and were a consequence of the overgrazing of common land by sheep and the farming of rabbits for meat and fur. These land-use practices de-structured the coversand and sparse vegetation that acted to stabilise the sands. The effect of this is most easily demonstrated by the infamous Great Sand Blow of the 1660s when the coversand sheet around Lakenheath became remobilised leading to the gradual eastwards creep of a large dune field which engulfed Santon Downham and parts of Brandon.

4.6.5 Palsas

At Thompson Common [TL 901 948] and Stow Bedon Common in the northern sector of the survey area a series of at least 40 small, circular ponds occupies the present valley bottom of an east-west trending tributary of the River Wissey (Figure 12). Traditionally, these features have been interpreted as pingos and, as a result, a popular walking route called the 'Great Eastern Pingo Trail' has been established. Because there are no rampart structures associated with these landforms – a morphological feature typical of pingo development, it is considered that the interpretation of these landforms as pingos may be erroneous. Instead, it is considered that the clustering and nature of these landforms is more commonly associated with another type of periglacial landform called palsas (palsa = singular). In modern areas of permafrost such as the Canadian high arctic and northern Finland, palsas typically form in wetland environments (e.g. marshes, valley bottoms) where discontinuous permafrost develops within peat-rich sediments. The development of segregated ice in peat-rich sediments causes doming – a palsa. Upon decay of the permafrost, caving and slippage at the base of the palsa leads to landscape inversion and the formation of a small basin. In the case of the landforms at Thompson and Stow Bedon commons, these basins have been occupied by small ponds. On the geological map, the valley bottom around Thompson Common and Stow Bedon Common is shown as peat, with the infill of the ponds shown as lacustrine deposits.

5 Artificial Ground

Artificial ground is present within certain areas of the Thetford survey area including the urban centres of Thetford and Brandon. The recent landscape history of RAF Lakenheath is not known with any certainty although parts have clearly been extensively disturbed and landscaped. One of the most striking artificial features is the levees bordering the lower reaches of the Little Ouse and its flood channel.

6 Conclusions

The principal findings of the modern survey of the superficial geology within the Thetford District are:

- The Chalk bedrock surface is highly variable in its form. Its generalised form is a function of erosion by Quaternary ice sheets – both directly and by glacial meltwater, together with the erosive action of modern and ancient rivers that have created major incised river valleys. At a local scale, the form of the Chalk bedrock surface is highly weathered and irregular in nature – a function of periglacial activity, dissolution and salt re-crystallisation.
- Many concealed valleys that have no surface expression were identified within the District and include both ancient river valley and narrow valleys eroded by subglacial meltwater. They typically contain thick and highly variable Quaternary successions.
- Detailed surveying and laboratory analyses demonstrate that the extent of till (boulder clay) within the survey area was considerably over-estimated on the 'Old Series' geological map.
- A veneer of coversand blankets almost all of the survey area. Chalk bedrock underlying this coversand layer is highly susceptible to weathering.

References

The British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

ARTHURTON, R.S., BOOTH, S.J., MORIGI, A.N., ABBOTT, M.A.W. AND WOOD, C.J. 1994. *Geology of the Country around Great Yarmouth, Sheet Memoir 162.* British Geological Survey, HMSO, London.

ASHTON, N.M., BOWEN, D.Q., HOLMAN, J.A., HUNT, C.O., IRVING, B.H., KEMP, R.A., LEWIS, S.G., MCNABB, J., PARFITT, S.A. AND SEDDON, M.B. 1994. Excavations at the Lower Palaeolithic site at East Farm, Barnham, Suffolk, 1989-92. *Journal of the Geological Society of London,* Vol 151, 599-605.

ASHTON, N.M., LEWIS, S.G., PARFITT, S.A., CANDY, I., KEEN, D.H., KEMP, R.A., PENKMAN, K., THOMAS, G.N. AND WHITTAKER, J.E. 2005. Excavations at the Lower Palaeolithic site at Elveden, Suffolk, UK. *Proceedings of the Prehistoric Society*, Vol. 71, 1-61.

BADEN-POWELL, D.F.W. 1948. The Chalky Boulder Clays of Norfolk and Suffolk. *Geological Magazine*, Vol. 85, 279-296.

BATEMAN, M.D. AND GODBY, S.P. 2004. Late-Holocene inland dune activity in the UK: a case study from Breckland, East Anglia. *The Holocene*, Vol. 14, 579-588.

BRITISH GEOLOGICAL SURVEY, 2010. Thetford. England and Wales Sheet 174 Bedrock and Superficial Deposits. 1: 50,000, Keyworth, Nottingham, British Geological Survey.

CANDY, I., COOPE, G.R., LEE, J.R., PARFITT, S.A., PREECE, R.C., ROSE, J. AND SCHREVE, D. 2010. Pronounced warmth during early Middle Pleistocene interglacials: Investigating the Mid-Bruhnes Event in the British terrestrial sequence. *Earth Science Reviews*, Vol 103, 183-196.

CATT, J.A. 1977. Loess and coversands. In: Shotton, F.W. (ed.). *British Quaternary studies: recent advances.* Clarenden, Oxford, 221-220.

CLARKE, M.R. AND AUTON, C.A. 1982. The Pleistocene history of the Norfolk-Suffolk borderlands. *Institute of Geological Sciences Report*, Vol. 82/1, 23-39.

CLAYTON, A.R. 1983. The sand and gravel resources of the country between Mildenhall and Barrow, Suffolk: description of 1:25 000 sheets TL76, 77 and part of 87. *Mineral Assessment Report, No.123*, Institute of Geological Sciences.

CLAYTON, K.M. 2000. Glacial erosion of the Wash and Fen basin and the deposition of the chalky till of eastern England. *Quaternary Science Reviews*, Vol. 19, 811-822.

FLOWER, J.W. 1869. On some recent discoveries of flint implements of the drift in Norfolk and Suffolk, with observations on the theories accounting for their distribution. *Quarterly Journal of the Geological Society, London*, Vol. 25, 449-460.

GALLOIS, R.W. 1994. *Geology of the country around King's Lynn and The Wash*. Memoir for 1:50,000 geological sheet 145 and 129. British Geological Surevy, HMSO, London.

GIBBARD, P.L., PASANEN, A.H., WEST, R.G., LUNKKA, J.P., BOREHAM, S., COHEN, K.M. AND ROLF, C. 2009. Late Middle Pleistocene glaciation in East Anglia, England. *Boreas*, Vol. 38, 504-528.

HOARE, P.G., STEVENSON, C.R., GODBY, S.P. 2002. Sand sheets and ventifacts: the legacy of aeolian action in west Norfolk, UK. *Proceedings of the Geologists' Association*, Vol. 113, 301-317.

HOPSON, P.M. AND BRIDGE, D. MCC. 1987. Middle Pleistocene stratigraphy in the Lower Waveney Valley, East Anglia. *Proceedings of the Geologists' Association*, Vol. 98, 171-185.

JERWOOD, L.C., ROBINSON, D.A. AND WILLIAMS, R.B.G. 1990. Experimental frost and salt weathering of Chalk – II. *Earth Surface Processes and Landforms*, Vol. 15, 699-708.

LEE, J.R., ROSE, J., RIDING. J.B., HAMBLIN, R.J.O. AND MOORLOCK, B.S.P. 2002. Testing the case for a Middle Pleistocene Scandinavian glaciation in Eastern England: evidence for a Scottish ice source for tills within the Corton Formation of East Anglia, UK. *Boreas*, Vol. 31, 345-255.

LEE, J.R., ROSE, J., HAMBLIN, R.J.O. AND MOORLOCK, B.S.P. 2004. Dating the earliest lowland glaciation of eastern England: the pre-Anglian early Middle Pleistocene Happisburgh Glaciation. *Quaternary Science Reviews*, Vol. 23, 1551-1566.

LEWIS, S.G. 1993. The status of the Wolstonian Glaciation in the English Midlands and East Anglia. Unpublished PhD thesis, University of London.

MATHERS, S.J. 1988. Geological notes and local details for 1:10 000 sheets TM08NW, NE, TM09SW,SE and parts of TL 98NE and TL99SE (Kenninghall, Banham, Attelborough and Old Buckenham): part of 1:50,000 sheet 175 (Diss): British Geological Survey. Onshore Geology Series, Technical Report, WA/88/040, 21pp.

NORFOLK GEODIVERSITY PARTNERSHIP, 2010. *Norfolk's Earth Heritage – valuing our Geodiversity.* Interprint, Norwich.

PERRIN, R.M.S., DAVIES, H. AND FYSH, M.D. 1974. Distribution of late Pleistocene aeolian deposits in eastern and southern England. *Nature*, Vol. 248, 320-324.

PERRIN, R.M.S., ROSE, J. AND DAVIES, H. 1979. The distribution, variation and origins of pre-Devensian tills in eastern England. *Philosophical Transactions of the Royal Society of London*, Vol. B287, 535-570.

RIDING, J.B. 2008. A palynological investigation of the Quaternary succession around Thetford, Norfolk, UK. *British Geological Survey Internal Report*, IR/08/006, 12pp.

ROSE, J. 1989. Tracing the Baginton-Lillington Sands and Gravels from the West Midlands to East Anglia. In: KEEN, D.H. (ed.). *The Pleistocene of the West Midlands, Field Guide*. Quaternary Research Association, Cambridge, 101-109.

ROSE, J., MOORLOCK, B.S.P. AND HAMBLIN, R.J.O. 2001. Pre-Anglian fluvial and coastal deposits in Eastern England: lithostratigraphy and palaeoenvironments. *Quaternary International*, Vol. 79, 5-22.

ROSE, J., WHITEMAN, C.A., ALLEN, P. AND KEMP, R.A. 1999. The Kesgrave sands and gravels: 'pre-glacial' Quaternary deposits of the River Thames in East Anglia and the Thames Valley. *Proceedings of the Geologists' Association*, Vol. 110, 93-116.

WATT, A.S., PERRIN, R.M.S. AND WEST, R.G. 1966. Patterned ground in Breckland: structure and composition. *The Journal of Ecology*, Vol. 54. 239-258.

WEST, R.G. 2007. The Little Ouse River, the Waveney River and the Breckland: a joint history. *Transactions of the Suffolk Naturalists' Society*, Vol. B43, 35-39.

WEST, R.G. AND DONNER, J.J. 1956. The glaciations of East Anglia and the east Midlands: a differentiation based upon stone orientation measurements of the tills. *Quarterly Journal of the Geological Society, London*, Vol. 112, 69-91.

WHITAKER, W, WOODWARD, H B, BENNETT, F J AND SKERTCHLY, S B J. 1881. The Geology of parts of Cambridgeshire and Suffolk (Ely, Mildenhall, Thetford) (Sheet 51NE with part of 51NW). Memoir of the Geological Survey of Great Britain.

WILLIAMS, R.B.G. 1964. Fossil patterned ground in eastern England. *Biuletyn peryglacjalny*, Vol. 14, 337-349.

WOODLAND, A.W. 1942. Water supply from underground sources, Cambridgeshire and Ipswich Districts. *Geological Survey, Wartime Pamphlet*, Vol. 20, Part IV, 33-55.

WOODLAND, A.W. 1970. The buried tunnel-valleys of East Anglia. *Proceedings of the Yorkshire Geological Society*, Vol. 37, 521-528.

WYMER, J.J. 1985. *Palaeolothic sites of East Anglia*. Geobooks, Norwich.