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The Fylde, Lancashire: Summary of the Quaternary Geology

Groundwater Programme

Open Report OR/16/013

BRITISH GEOLOGICAL SURVEY

GROUNDWATER PROGRAMME

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The Fylde, Lancashire: Summary of the Quaternary Geology

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The model fence diagram looking towards the north.

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Foreword

The British Geological Survey (BGS), together with a number of partners is undertaking an independent environmental monitoring programme to characterise baseline conditions in the south Fylde, east of Blackpool in an area proposed for shale-gas exploration and production. The monitoring will include measurement of: water quality (groundwater and surface water), seismicity, ground motion, air quality including radon, and soil gas. The programme aims to establish the environmental baseline before any shale-gas drilling begins.

This report presents the results of a desk study to develop an initial summary of the Quaternary (Superficial) geology of the south Fylde. The south Fylde area is mantled by unconsolidated material of variable thickness and composition that is locally in excess of 40 m. In some areas, sub-glacial meltwater channels have been incised into the upper part of the bedrock, forming a network of buried, sediment-filled channels and intervening bedrock highs. Superficial Deposits are characterised by Till, Glaciofluvial Sand and Gravel and Glaciolacustrine Clay that were deposited during the Late Devensian glaciation, and Peat, Alluvium, Blown Sand and Marine and Coastal Deposits that accumulated during the Holocene. Within the Quaternary sediments there are a number of secondary aquifers. A separate report considers the bedrock geology (Newell, 2016).

The geological information in this report will form the basis for identifying recharge zones and potential pathways and connections between the surface and primary (Sherwood Sandstone bedrock) and secondary aquifers, and potential contaminant migration pathways in the shallow subsurface. It will also provide part of the geological framework within which the results of acquired hydrogeochemical data can be understood.

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Executive Summary

This report summarises the regional superficial (otherwise known as *Quaternary*) geology of the Fylde region, western Lancashire, with an emphasis on understanding the geological units in terms of potential fluid transport through the differing units. The study utilised existing geological maps and borehole records to construct a series of cross-sections traversing the area depicting the superficial deposits as a geological fence diagram.

Quaternary-age glacigenic deposits dominate the majority of geological units in the shallow subsurface. The glacigenic units comprise the following: 1) tills, which are composed of gravels in a dominantly clay-rich matrix; 2) glaciofluvial deposits, composed of gravels and sands; and 3) lesser amounts of glaciolacustrine deposits consisting of laminated clays and silts. The tills and glaciofluvial deposits are generally intercalated with one another, and are of variable thickness and lateral extent. The base of the sequence broadly comprises a basal till overlain by a glaciofluvial unit and in-turn, an upper till. However, there are major local variations to this succession with localised inclusions of sand, gravel, silt and clay. The units show a high lateral and vertical variability across short distances making it difficult to extrapolate lithologies to areas where boreholes are absent.

Along the coastal zone and within the tidal estuaries of the River Wyre and the River Ribble, coastal zone deposits occupy a thin surface layer. These Holocene-age deposits mainly comprise clays, silts and sands with some gravel.

Peat occurs throughout the region, but particularly along the ‘Skippool Channel’, east of the River Wyre south of Preesall, and in the subsurface from South Shore Blackpool, to Lytham St Anne’s and inland to Marton Moss.

The Kirkham moraine forms a broad and subtle topographic high in relief from Blackpool, eastward through Kirkham to Preston.

Lastly, a bedrock high has been found around Rawcliffe Moss, West of Churchtown in the north eastern edge of the model area. There may be other undiscovered zones of thin or absent superficial cover that may provide direct connectivity from the surface to the underlying bedrock.

1 Introduction

The Fylde is a flat lying area, part of the West Lancashire Plain, situated between the Bowland Hills to the east and the Irish Sea to the west. It is bordered to the south by the River Ribble and by Morecambe Bay to the north, and includes the popular coastal resorts of Lytham St Anne’s, Blackpool and Fleetwood (Figure 1). The current natural landscape of Fylde reflects the range of geological and geomorphological processes that have affected the region especially over the past 2.6 million years, i.e. the *Quaternary*. During this time-interval the region was affected by several Ice Ages and periods of sea-level change. However, much of the Quaternary geology relates to events that have occurred over the past 30,000 years including the Late Devensian glaciation (Figure 2) and the subsequent Holocene sea-level rise. Collectively, these events have left behind a sequence of unlithified strata that in places exceeds 40 metres thickness. These strata cover the uppermost bedrock units including mudstone (Mercia Mudstone Group) beneath the west of the region, and sandstone (Sherwood Sandstone Group) beneath the east.

Figure 1: Location of The Fylde model area (blue) and the drill sites proposed for hydraulic fracturing in connection with hydrocarbon exploration (purple crosshairs)

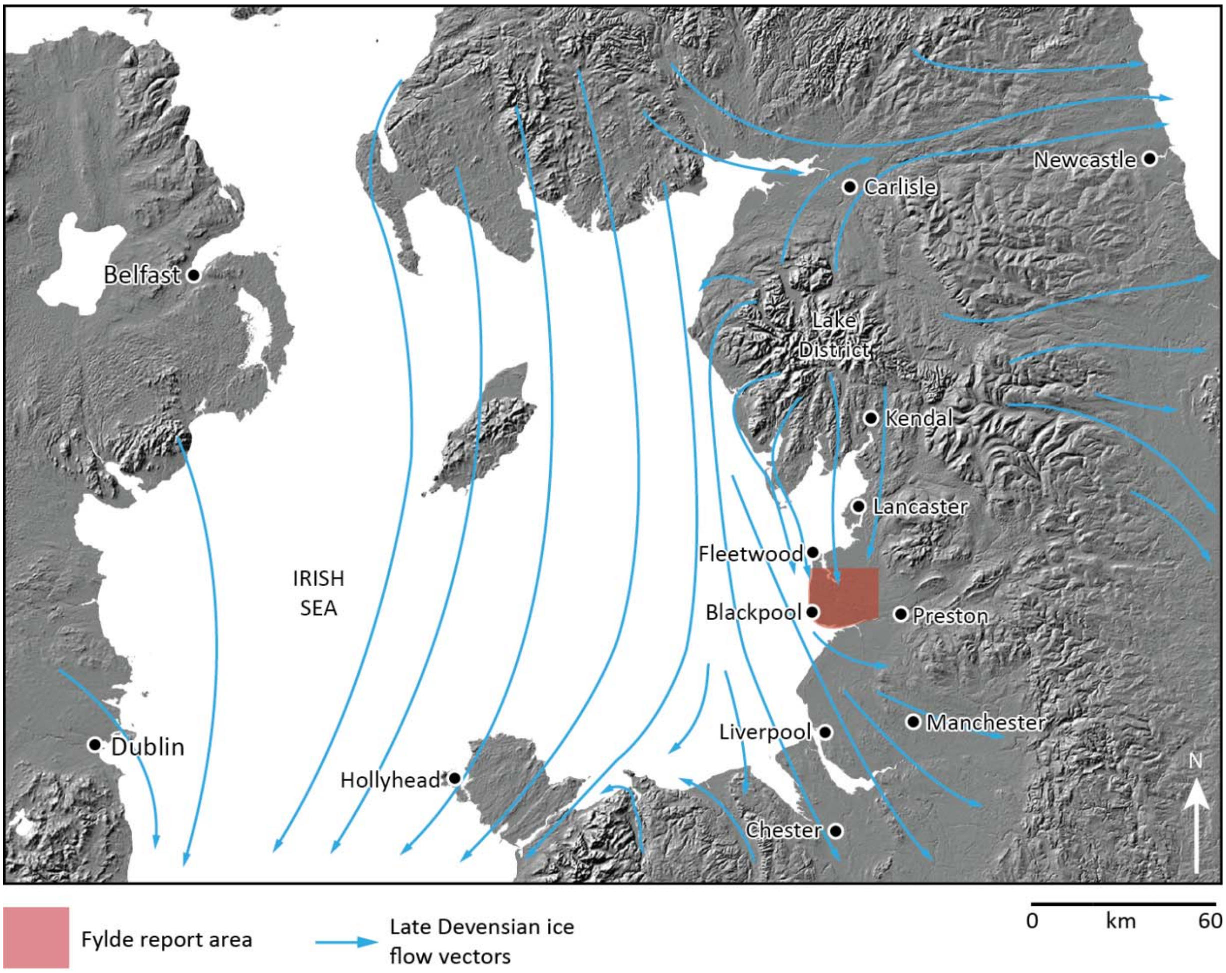


Figure 2 Location of the Fylde report area showing its broader context relative to the Late Devensian glaciation when the region was inundated by local glaciers emanating from the Lake District and the much larger Irish Sea Ice Stream (after Phillips et al., 2010). NEXTMap Britain elevation data from Intermap Technologies.

Recently, interest in the geology of the region has arisen because of the potential for commercially-exploitable shale gas within rocks that occur at significant depth beneath the area. As part of an assessment of the environmental sustainability and impact of exploitation, an independent groundwater monitoring programme is being undertaken by the British Geological Survey to monitor baseline groundwater chemistry around potential extraction sites and the wider region, before any exploration begins.

A key component of this monitoring is improving our knowledge of the geology within the shallow subsurface. Specifically, this report addresses the zone of geology that provides the link between the land-surface and bedrock encompassing both natural and anthropogenic unlithified Quaternary deposits. Within this report, a broad assessment of the regions, Quaternary deposits and features (excluding those of Anthropogenic origin) is undertaken with specific emphasis placed on identifying potential units that could represent groundwater flow-paths between and along the land surface and the bedrock.

2 The Quaternary history of Fylde: An overview of past work

Throughout the Quaternary, global climate has varied cyclically between extended periods of warmth (called interglacial stages) and cold (called glacial stages) that lasted tens-of-thousands of years. During interglacial stages, like the current Holocene interglacial which has spanned approximately the past 11,700 years, global ice volume has been low with high global sea-levels. In contrast, during glacial stages, global sea-levels have been much lower with more water locked-up within larger polar ice masses. Due to its location within the northeast Atlantic and proximity to polar and temperate air masses, the UK has been subjected to marked and repeated changes in climate, sea-level and geography. The Fylde area has also been subjected to these changes although geological evidence does not generally extend beyond the last glacial stage (Wilson and Evans, 1990).

The last glacial stage is known as the Late Devensian glaciation and occurred between about 29,000 and 11,700 years ago. For the first 14,000 years of this interval, much of northern Britain was covered by a vast ice sheet – the British-Irish Ice Sheet, which extended outwards from highland source areas into adjacent lowland and basinal areas (Clark et al., 2012; Livingstone et al., 2012). Several large fast-flowing glaciers called ice streams moved ice rapidly from the interior of the ice sheet to its margins. One such ice stream, the Irish Sea Ice Stream, extended southwards through the Irish Sea Basin from southern Scotland reaching the Isles of Scilly (Harris et al., 1997; Thomas et al., 2004; Hiemstra et al., 2006; Roberts et al., 2007; Hubbard et al., 2009; Phillips et al., 2010; Clark et al., 2012; Chiverrell et al., 2013; Phillips and Hughes, 2014; Lee et al., 2015). Regional ice dispersal centres, such as those situated in the Lake District, also fed ice outwards into the Irish Sea, Lancashire and northern England (Livingstone et al., 2012).

Central Lancashire and specifically the Fylde area, was situated along the transition zone between the Irish Sea and Lake District ice masses (Delaney, 2003; Chiverrell, 2012). A tripartite sequence comprising a lower till, middle sands and an upper till has been recognised within coastal sections at Blackpool (Binney, 1852; De Rance, 1877) and has been replicated regionally from borehole records (Wilson and Evans, 1990). The basal till, up to 7 metres thick, is highly consolidated and composed of a red clay (derived from the underlying Mercia Mudstone) with far-travelled erratic clasts that have a provenance in Cumbria and Mesozoic / Quaternary strata from beneath Morecambe Bay (Wilson and Evans, 1990). The middle sands attain thicknesses of 20 metres and are commonly inter-bedded with laminated silts and clays (Wilson and Evans, 1990). Their upper surface is undulating indicating a period of erosion either prior to or during deposition of the upper till. The upper till drapes over the irregular surface of the middle sands. It is composed of a highly-consolidated brown silty-clay with a wide range of erratic clasts and cobbles. Erratics include Lake District volcanic lithologies, granite, greywacke and Carboniferous sediments derived from northwest England (Wilson and Evans, 1990).

Over the years, there has been much discussion relating to the geological context of the tripartite glacial sequence and it is only in recent years that its significance has become clearer. In keeping with the early 'diluvial' theories of glaciation, which were popular during the nineteenth century, many early workers argued that the tills were the product of floating sea-ice with the intervening sands laid-down during a major sea-level rise (Binney, 1852; De Rance, 1877). More recently, geologists have proposed that the tills were deposited terrestrially by grounded ice and debate has focused upon whether the deposits are the product of one or two glacial stages (Carruthers, 1939). Important clues to the terrestrial origin of the sequence are provided by the range of glacial landforms that occur across the region (Johnson, 1985; Delaney, 2003). These include drumlins and other elongate landforms produced by the streamlining of sediment beneath a glacier (Wilson and Evans, 1990). These extend northwards around the margins of Morecambe Bay (including to the north-east of Blackpool) towards Lancaster and the Lake District (Delaney, 2003). In addition, to the south, the Kirkham Moraine forms a subtle but extensive west-east trending landform that represents the terminus of southwards flowing Lake District ice across the Fylde area (Johnson et al., 1972; Johnson, 1985; Delaney, 2003; Chiverrell, 2012). Upon retreat of the glacier, several lake basins formed across the area, represented by tracts of silt, clay and sand that occur discontinuously (Wilson and Evans, 1990). In areas where buried ice stagnated *in situ*, small basins called kettle holes developed (Chiverrell, 2012). Thin discontinuous spreads of windblown sand (known as coversand) were deposited across the Fylde region (Bateman, 1995). Their composition implies that they were derived locally by the deflation (wind erosion) of glacial outwash sand (Wilson et al., 1981).

Following the end of the last glaciation, the climate began to warm and sea-levels rose, marking the transition to the Holocene Interglacial (Tooley, 1974; Lambeck and Purcell, 2001). This resulted in the progressive drowning of the Irish Sea Basin with marine conditions extending eastwards beneath the western part of the Fylde. For instance, marine deposits have been recorded beneath Fleetwood, incised to depths of -22 metres OD into the upper surface of the glacial deposits (Wilson and Evans, 1990). In common with Holocene coastlines bordering North Wales, Cheshire and Lancashire the maximum elevation of marine deposits is approximately 4-5 metres OD (Greenly, 1919; Bedlington, 1994; Roberts et al., 2011). Their elevations reflect crustal adjustments (called isostatic rebound) following the removal of glacier ice from the landscape which have caused the land to progressively rise above sea-level (Lambeck and Purcell, 2001). Holocene coastal environments including sand dune systems are now well-developed along the western coastline of Fylde.

3 The Fylde 3D Geological Model

3.1 INTRODUCTION

To better our understanding of the distribution and associations of Quaternary deposits in the subsurface in this area, a fence diagram of the Quaternary geology was built using GSI3D© software (Kessler, H, and Mathers, S. 2004). Four cross-sections running from north to south, four cross-sections running west to east, along with two additional sections in the western part of the area (Figure 11) were constructed using the available geological data and expert knowledge. The process is described below.

3.2 UTILISED GEOLOGICAL DATA

3.2.1 Published geological map data

The study area is covered by four 1:50,000 scale geological map sheets (Figure 3): Blackpool (sheet no. 66), Garstang (67), Southport (74) and Preston (75). The Blackpool sheet was last surveyed in 1968 and was published in 1975. The Garstang sheet was last surveyed in 1984-8, with the Superficial Deposits (drift) edition published in 1991. The Southport sheet was last revised in 1986 and was published in 1989. The Preston sheet was last surveyed between 1980 and 2007 and was published in 2012.

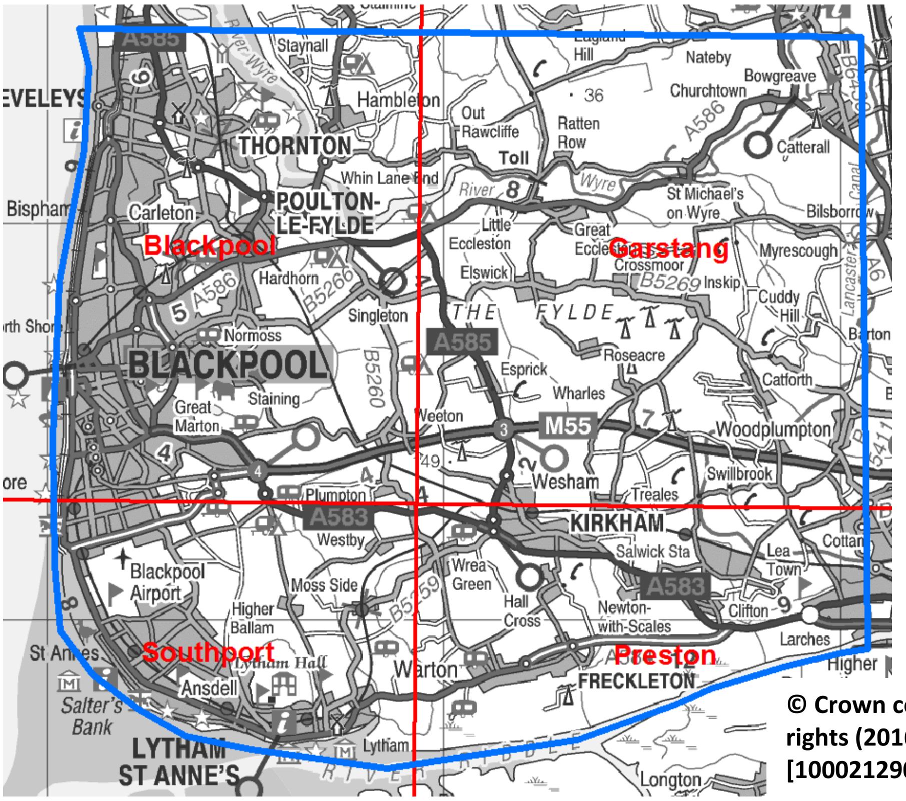


Figure 3 1:50,000 scale geological map sheets covering the study area (red), study area outlined in blue

Digital 1:50,000 scale geological map data were used for guidance in the cross-sections (Figure 4). This shows that the most widespread Quaternary unit at surface is till, with associated glaciofluvial deposits forming linear outcrops. Holocene aged alluvium associated with the floodplain of the River Wyre is present in the northern part of the study area. Tidal flat deposits dominate in coastal areas and are mapped in the tidal reaches of rivers. Large areas of peat are mapped in the north of the study area, as well as a roughly north-south tract through the west. An extensive area of cover sand is mapped around Blackpool and Lytham St Anne's. Head Deposits infill some of the shallow valleys in the southern part of the study area, around Kirkham.

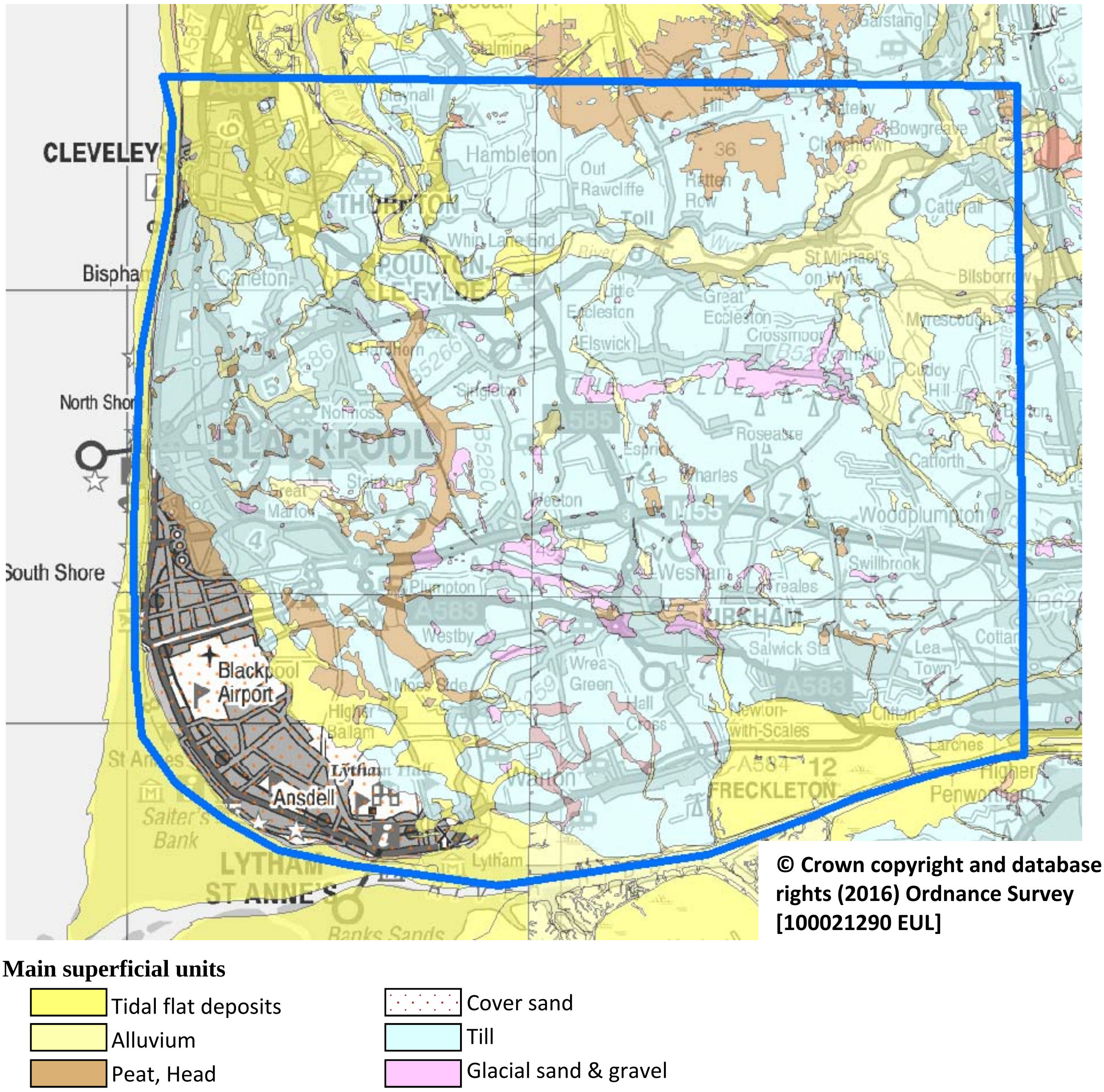


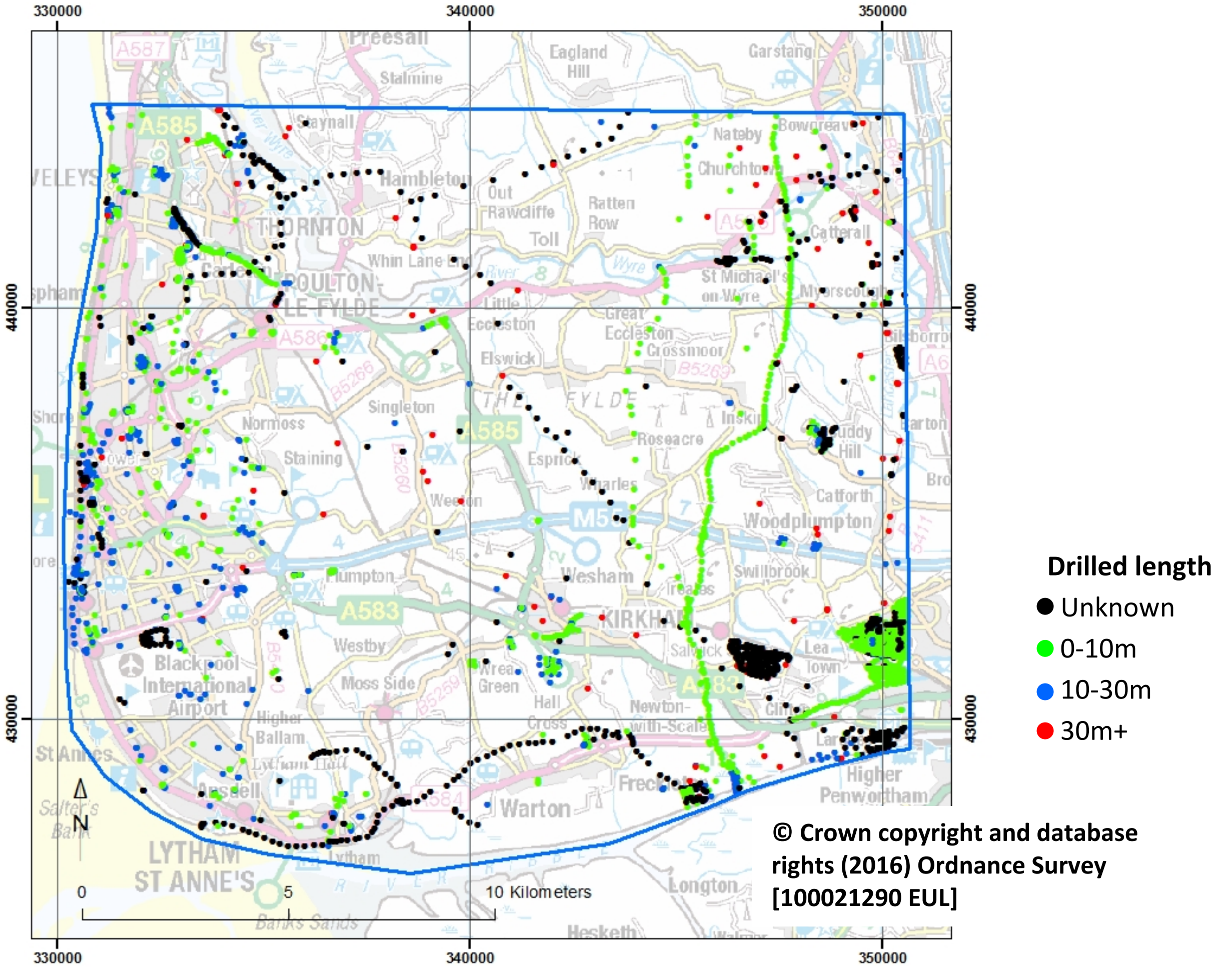
Figure 4 Superficial geology map showing DiGMapGB-50, study area outlined in blue. 10km grid squares shown on the topographic map

3.2.2 Borehole data

The BGS holds 2949 records of boreholes and trial pits within the study area, some of which are shallow and provide no useful data for the purposes of aiding the understanding of the Quaternary geology. However, the majority of the boreholes hold useful information regarding the composition and stratigraphic relations of these deposits. 172 boreholes were used in the cross-sections, out of 202 boreholes that were coded. To enable these borehole data to be viewed in the 3D modelling software, geological information from the borehole logs were 'coded' into the corporate *Borehole Geology* database. Approximate positions of the cross-section lines were plotted prior to coding the boreholes using the distribution and drilled length of borehole data for guidance to select the best available logs in the study area. Boreholes were selected for coding based on their drilled length and the level of detail recorded in the logs.

Boreholes that reach rockhead, as well as boreholes that provide detailed descriptions of the Quaternary succession, were preferentially selected. Figure 5 shows the distribution of boreholes in the study area. A list of the boreholes used to construct the cross-sections and their location is provided in Appendix 1.

Figure 5 Distribution of borehole data, study area outlined in blue.



3.2.3 Rockhead and Superficial Drift Thickness models

The National Rockhead Elevation Model (Lawley and Garcia-Bajo, 2009) was used as a guide to the position of the base of the Quaternary sequence during cross-section correlation. Where borehole data proved rockhead at a different depth, the information from the boreholes was used instead (Figure 6).

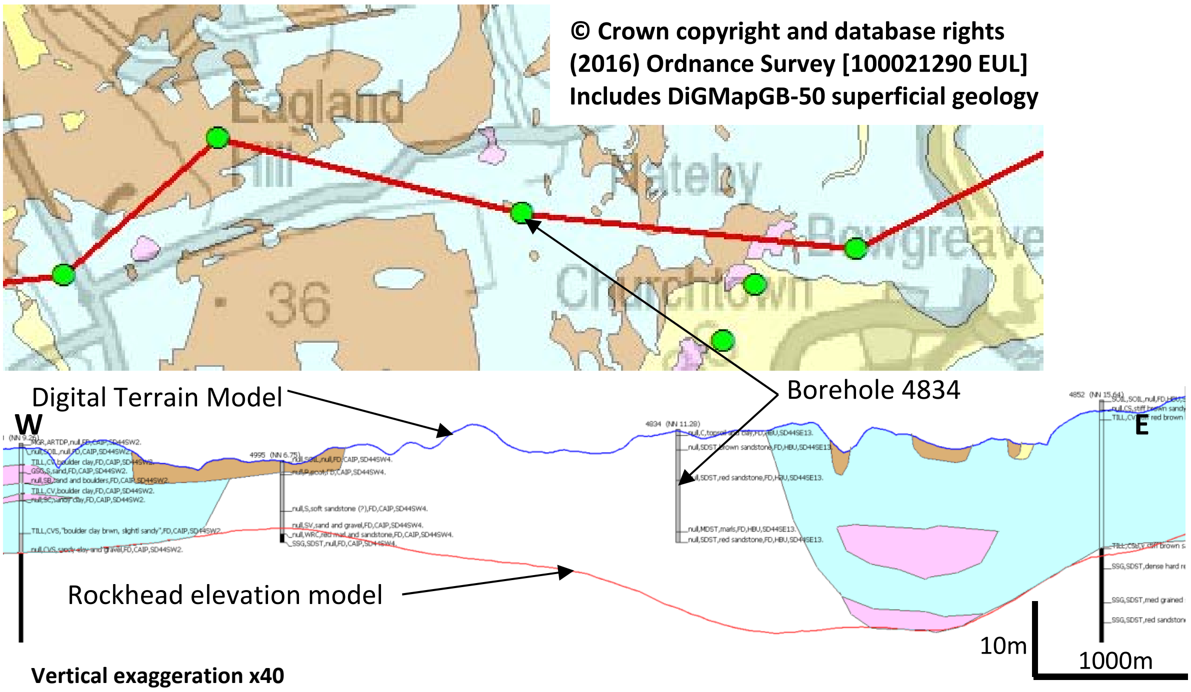


Figure 6 **Extract from the eastern part of cross-section W_E_Section_4_FYLDE_HBU showing mapped till and peat deposits where borehole evidence proves bedrock at surface**

The limitations of the national rockhead elevation model are discussed further in the Data Limitations section of this report (Section 5.2.4). Figure 7 shows an extract from the national rockhead elevation model, which ranges from +109.87 to -59.40m in the study area. Areas of highest rockhead elevation occur in the eastern part of the area are shown in red and areas of lowest elevation, predominantly in the central and western parts of the area are coloured blue.

Figure 7 shows an extract from the NextMap Britain 'Bald Earth' digital elevation model (DTM) from Intermap Technologies, which was used as a capping surface for the cross-sections. A comparison between the rockhead elevation model and the Bald Earth DTM shows that the elevation of rockhead broadly follows topographic features.

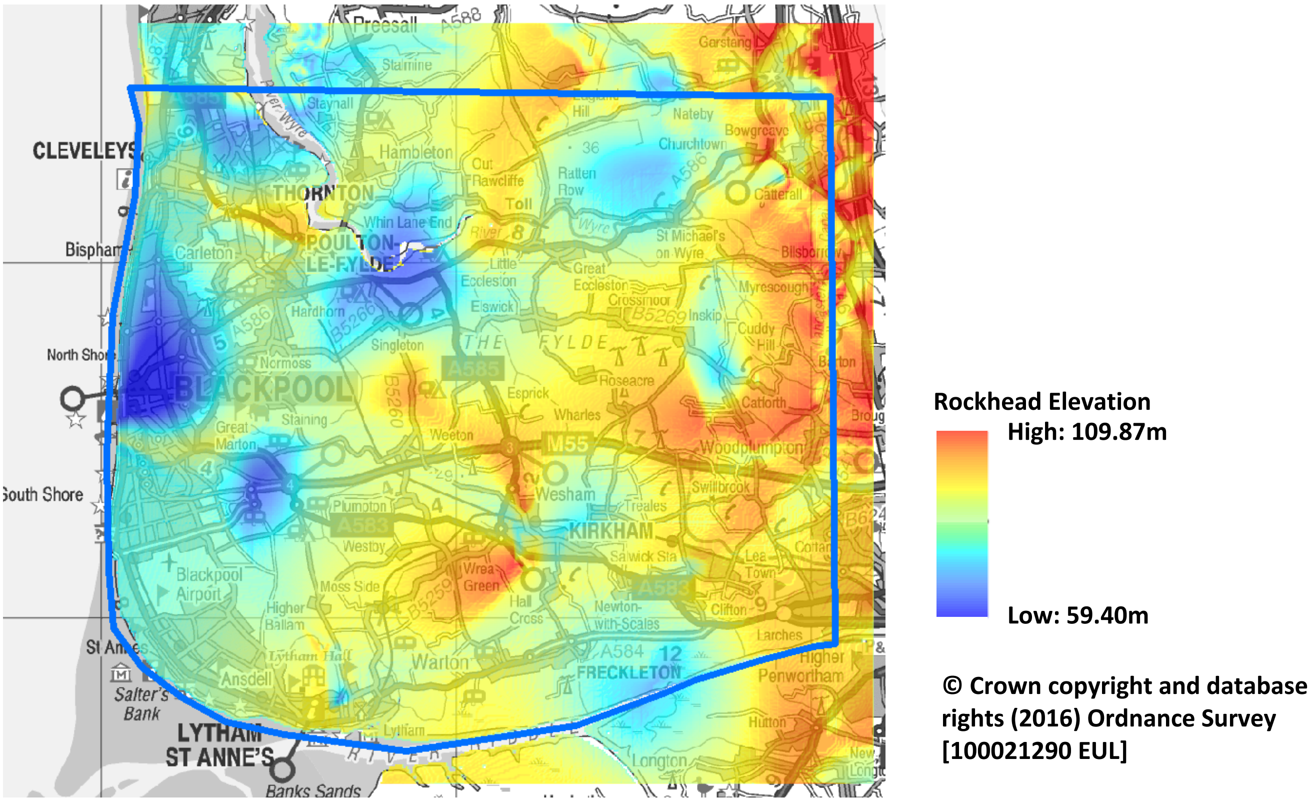


Figure 7 Extract from the BGS National Rockhead Elevation Model shown with a red to blue colour ramp, study area outlined in blue. 10km grid squares shown on the topographic map

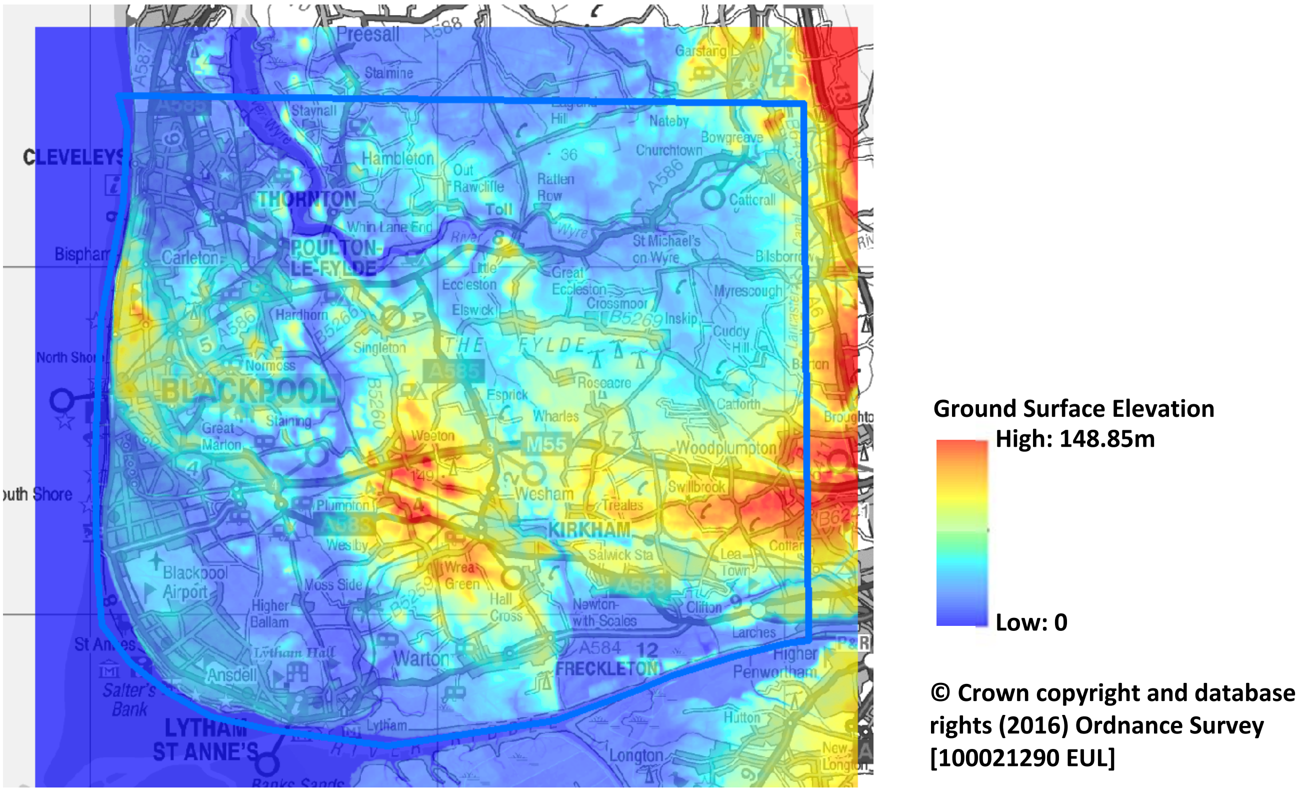


Figure 8 Extract from the 'Bald Earth' digital terrain model shown with a red to blue colour ramp, study area outlined in blue. 10km grid squares shown on the topographic map. The Kirkham Moraine can be seen by the yellow and red colours, traversing the area from Blackpool, going east through Kirkham towards Preston.

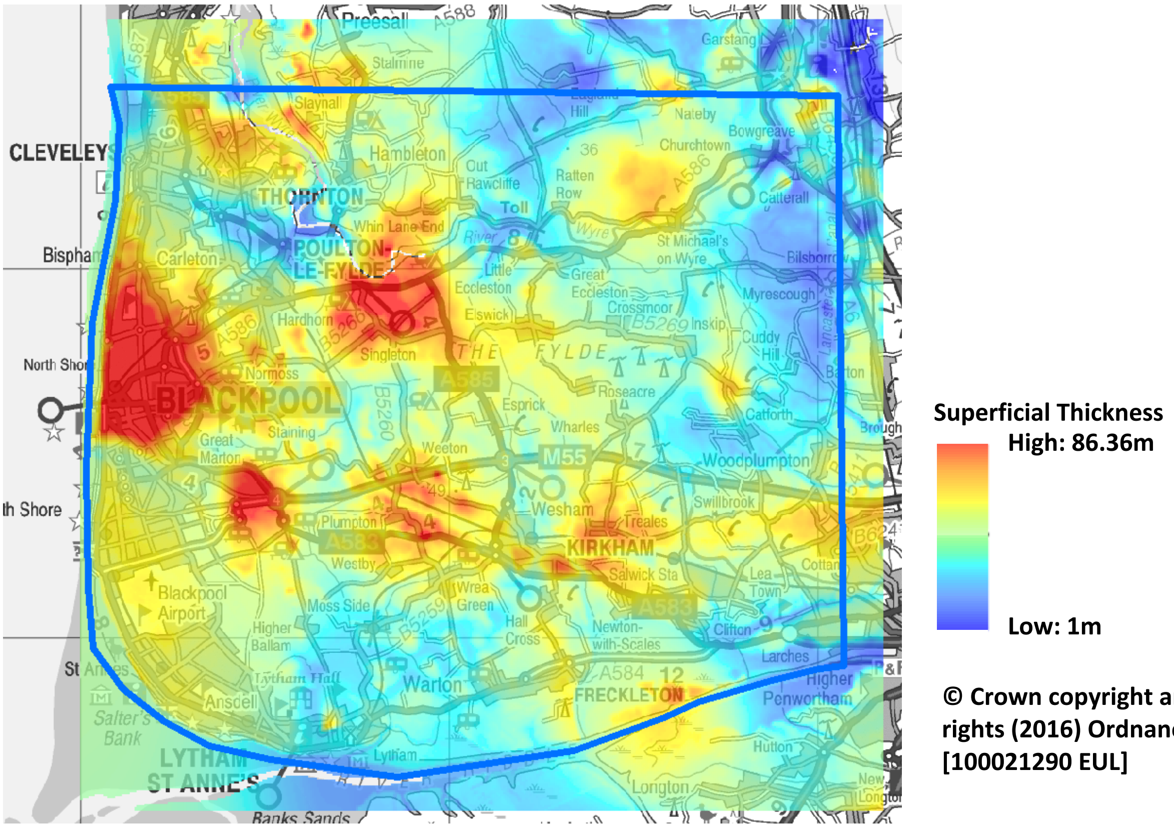


Figure 9 Extract from the BGS National Superficial Deposits Thickness model shown with a red to blue colour ramp, study area outlined in blue. 10km grid squares shown on the topographic map

3.2.4 Data Limitations

One limitation of this study is the density of borehole data used to underpin the correlated cross-sections. The boreholes in the BGS Single Onshore Borehole Index that lie within the study area are concentrated around urban areas and along transport and infrastructure routes, leaving gaps, particularly in rural areas. In the absence of borehole data, the rockhead elevation model and geological map data are used in the cross-sections. Complexity within the glacial sequence, such as sand and gravel lenses, is only modelled around the boreholes where proven, and may actually be more prevalent.

The borehole logs themselves vary in the level of detail recorded, depending on the purpose of the borehole. Some boreholes provide little detail on the Quaternary, examples include borehole 2288, which records ‘boulder clay’ (till) to a depth of 34.14m, without providing a description or recording any lithological variability, but gives a very detailed record of the bedrock. This borehole is still useful for proving rockhead information.

The geological map data were validated during cross-section correlation using borehole evidence. Priority was given to the boreholes in cases where mismatches occurred between the boreholes and the geological map data. For example, cross-section W_E_Section_4_FYLDE_HBU runs west to east across the north of the study area where extensive till and peat deposits are mapped. However, borehole 4834 in this cross-section records Sherwood Sandstone Group bedrock at the ground surface. The borehole evidence was honoured in the cross-section and a bedrock ‘high’ is represented at this locality.

The Quaternary cover locally exceeds 30m in thickness and many of the boreholes do not prove rockhead.

3.3 THE CROSS-SECTIONS

The location of the cross-sections and drill sites of Roseacre and Preston New Road are given in Figure 11. The boreholes used are shown by red dots with the legend providing the cross-section names. The cross-sections are presented, all with an x25 vertical exaggeration, and the location of the drill sites are given, where applicable. Cross-section legends are given in Figure 10.

3.4 THE MODELLED UNITS

The modelled units can be broadly grouped into three categories: post-glacial terrestrial units, marine and coastal units, and glacial units. In general, post-glacial deposits inhabit a narrow (less than 10m thick) zone at the top of the cross-sections, and could be absent, whilst the bulk of the sections are made up of glacial deposits. Within the glacial deposits, there is a wide variation in the spatial distribution of the units, and the 'tripartite subdivision' of till to glaciofluvial sands and gravels to till (e.g., Price et al., 1963), does not necessarily hold true. The individual section images provide further details on the spatial distribution of the glacial deposits.

What follows below is a brief description of the typical lithological composition of the modelled units. The legend is given in Figure 10.

3.4.1 Post-glacial terrestrial deposits:

Alluvium:

This unit occurs at surface in low-lying ground around, along the base of river and stream valleys and in small isolated patches associated with glacial deposits. It occurs in the floodplain along the River Wyre, and it is particularly extensive in the north eastern corner of the model area around Myerscough, where it forms a large expanse between tributaries to the River Wyre. The eastern portion of Section W_E_3_Fylde_HBU crosses through a large segment of this area.

Alluvium has a variable lithology, depending on conditions of deposition. It can be composed of differing amounts of clay, silt, sand and gravel, and in general, is up to 2-5m thick, but there potentially could be wide local variations in this estimation.

Peat:

Peat and is mapped at surface and at depth within several boreholes. It is proven in boreholes as a major unit (i.e. the unit is principally composed of peat) and as minor and localised constituent within other deposits. (See section 5.5.2 for more details on the occurrence on peat in the Fylde area).

Head:

Head is a type of slope deposit that occurs as small isolated patches on sloping ground, and has been recorded where it exceeds a metre thickness. It comprises a mixture of clay, silt sand and gravel (depending on parent material) in varying proportions. Head deposits occur in the south of the model area, and are particularly concentrated along section W_E_1_Fylde_HBU. Due to the nature of the head formation in the geologic recent past, it is very unlikely to occur at depth concealed beneath other units.

3.4.2 Post-glacial marine and coastal deposits:

Tidal flat deposits:

Modern tidal flat deposits occupy the intertidal zone along the coastline. They are particularly extensive around the coastline offshore from Lytham St Anne's, and extend inland under the Blown Sand unit (see below). This is shown in sections W_E_1_Fylde_HBU and W_E_2_Fylde_HBU and the Coast_Helper1_HBU. Tidal flat deposits are generally composed of a grey silt and clay, and are likely to be in the range of 2-18m thick. Additionally, Section W_E_1_Fylde_HBU records a maximum tidal flat thickness of 18m.

Additional tidal flat deposits reach inland, and they occur in a large surface zone south of Fleetwood, and in a zone reaching inland from the river Ribble in the south. They are composed of silt and clay, with the local addition of sand and possible peat layers, and are in the order of 1-15m in thickness.

Storm Beach deposits (included Raised Storm Beach Deposits):

Storm beach deposits are a modern deposit and occur as a narrow strip following the present day coastline around Cleveleys and Lytham St Anne's. They have a bank-like form and are composed of unconsolidated gravel without significant matrix material.

Raised storm beach deposits were deposited and also have a bank like form. They are two very small units in the model area, one immediately south of Preesall in the north of the model area, and one inland from the River Ribble in the south. They are composed of poorly consolidated sands gravels.

Blown Sand:

Blown sand occurs at surface predominately in the Blackpool to Lytham St Anne's coastal area and reaches 2.5-3km inland. It is composed of well sorted, fine to medium grained sand, deposited by wind action. It is generally up to 10m thick, and is present in sections W_E_1_Fylde_HBU and W_E_2_Fylde_HBU and the Coast_Helper1_HBU.

Tidal River or Creek Deposits:

This occurs as a modern (tidal) river intertidal zone deposit of the River Ribble in the south of the model area, around Freckleton. It is restricted to a very narrow, approximately 200-250m wide, zone adjacent to the River Ribble. The deposits are composed of soft clay, silt and sand. They are shown in the extreme southern end of sections N_S_2_Fylde_CAIP, N_S_3_Fylde_CAIP and N_S_4_Fylde_CAIP and are approximately 1-5m thick.

Saltmarsh Deposits:

Like tidal river or creek deposits above, modern saltmarsh deposits occur at surface in a thin zone along the River Ribble in the south of the model area. They are most extensive at Warton Bank and are composed of sand, silt and clay with organic debris. They are likely to be 1-5m in thickness.

3.4.3 Glacial deposits:

Glaciolacustrine Deposits

Glaciolacustrine deposits occur at depth within the glacial sequence, and are predominantly composed of laminated clays and silts (but may contain isolated clasts of coarser grained material). The units are generally modelled as isolated lenses within the glacial sequence and are common, occurring in most sections.

Glaciofluvial Deposits:

Glaciofluvial deposits comprise well sorted and often free-running, sands and gravels. In section, they are laterally extensive and occur in all sections, often reaching considerable thicknesses. For example, in section N_S_1_Fylde_CAIP a borehole proves there to be around 45m of glaciofluvial sands and gravels. The bounding geometries of glaciofluvial units are likely to be highly irregular and with frequent intercalations with other units, particularly with the till and glaciolacustrine units due to their environment of deposition. Glaciofluvial deposits occur in all sections.

Till:

Till is the most extensive of the glacial deposits, and is found in all sections. Till lithologies can be typically described as reddish, ill-sorted mixture of firm to stiff clay/sandy matrix with scattered gravel (and less frequently, with coarser grain sizes such as cobbles and boulders). The till matrix lithology found predominately on Sherwood Sandstone Group comprises clayey sand or sandy clay matrix, and on Merica Mudstone Group, it is predominately clay-rich. The till unit is locally intercalated with other glacial units, particularly the glaciofluvial deposits. It can also occur as isolated lenses within glaciofluvial or glaciolacustrine deposits.

Figure 10 Legend for the superficial geology in the cross sections

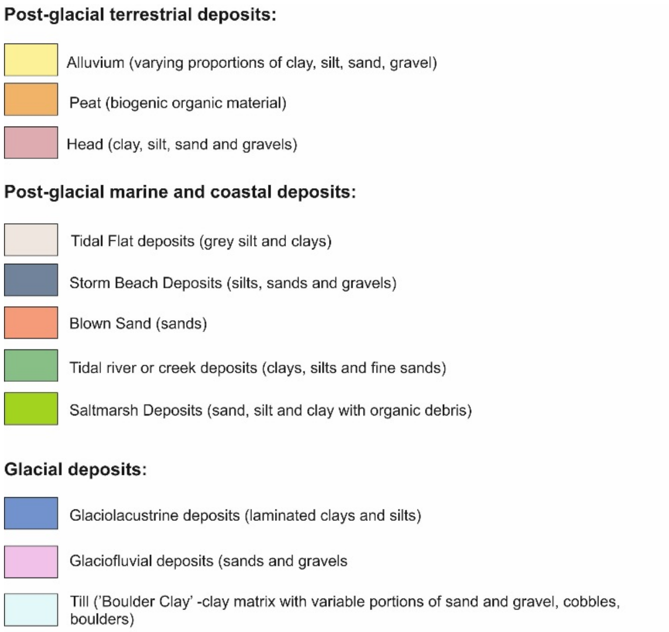
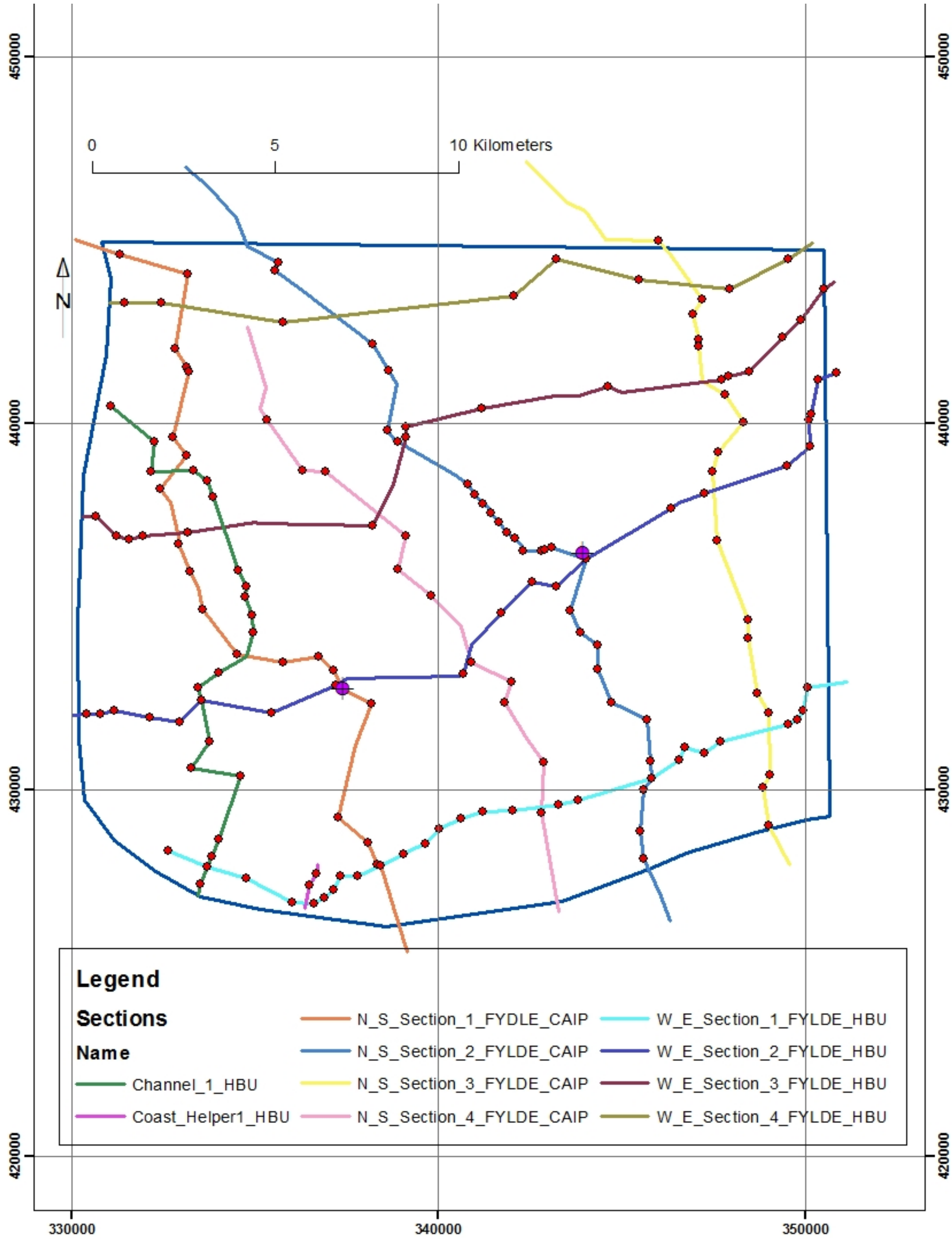


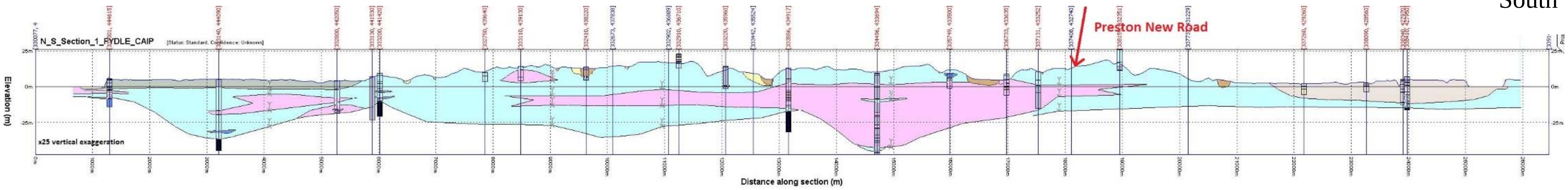
Figure 11 Map of the model area (blue outline) showing cross-section location with boreholes (red dots) and the drill sites (purple cross-hairs)



3.4.4 North-South sections

3.4.4.1 N_S_SECTION_1_FYLDE_CAIP

North South

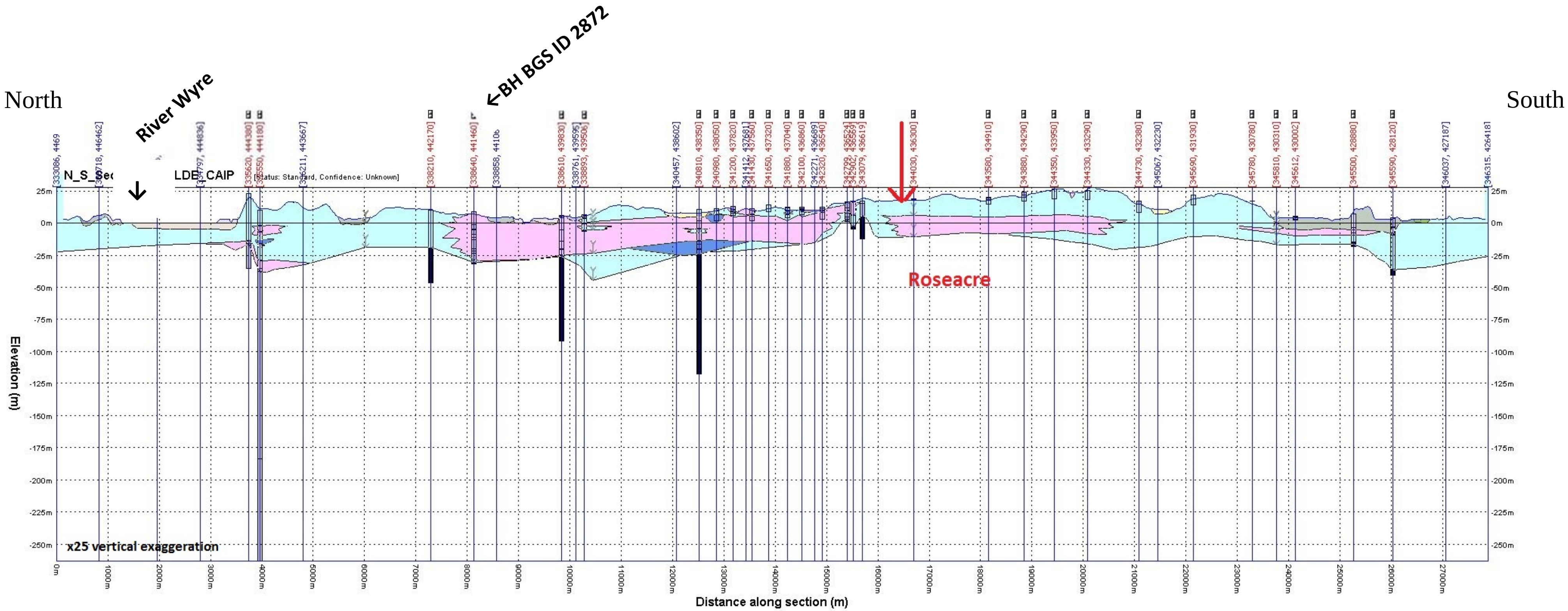


This section runs north to south from the coast at Cleveleys, skirting the edge of Blackpool, then swings inland and crosses the Preston New Road site (marked by an arrow in the above section). It then continues south and crosses Westby and Mosside and terminates on the banks of the River Ribble (Figure 11). Horizontal grid lines are at 1km intervals, and vertical gridlines are at 25m intervals. There is a 25m vertical exaggeration (and this follows for all the subsequent sections).

The Quaternary geology here shows that the glacigenic units of till (pale blue) and glaciofluvial units (pink) dominate the succession. Of particular note, is a circa 45m thick glaciofluvial unit comprising fine gravels, gravels, sands and lesser amounts of cobbles and boulders (BGS borehole ID 2306). This unit is thought to extend to beneath the Preston New Road site. The lateral extent of this unit to the north is harder to constrain due to the lack of borehole data.

The pale grey unit in the south of the section is a tidal flat deposit that contains a peat unit of around 1-1.5m thickness. It lies 1-3m below the surface and is proved in boreholes shown on the section (BGS ID 1283, 1216, 1274). Also see section 5.5.3 for additional information regarding peat.

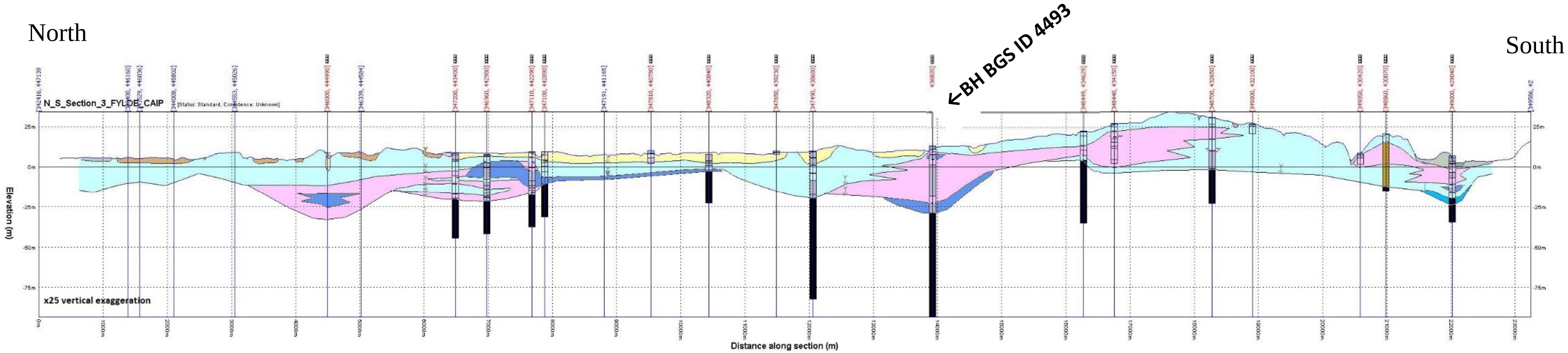
3.4.4.2 N_S_SECTION_2_FYLDE_CAIP



This section runs north to south from Fleetwood in the north, runs south-easterly through the Roseacre site (location marked with a red arrow), and south to Kirkham and terminates at the River Ribble near Freckleton (Figure 11). The gridlines are 1km horizontal spacing and 25m vertical spacing.

The section is dominated by glacial units of till (light blue) and glaciofluvial deposits (pink). There is a thick glaciofluvial unit to the north of the Roseacre site, including a lens of glaciolacustrine clay. The glaciofluvial unit reaches 40m thickness in borehole BGS ID 2872. Apart from a 10m thick unit of 'sand and clay' at the top of this borehole, the majority of borehole superficial deposit consists of sand with subordinate amounts of gravel, and this lies directly on bedrock (of Mercia Mudstone Group). The Roseacre site consists of till over glaciofluvial deposits, and this is about 30m thick.

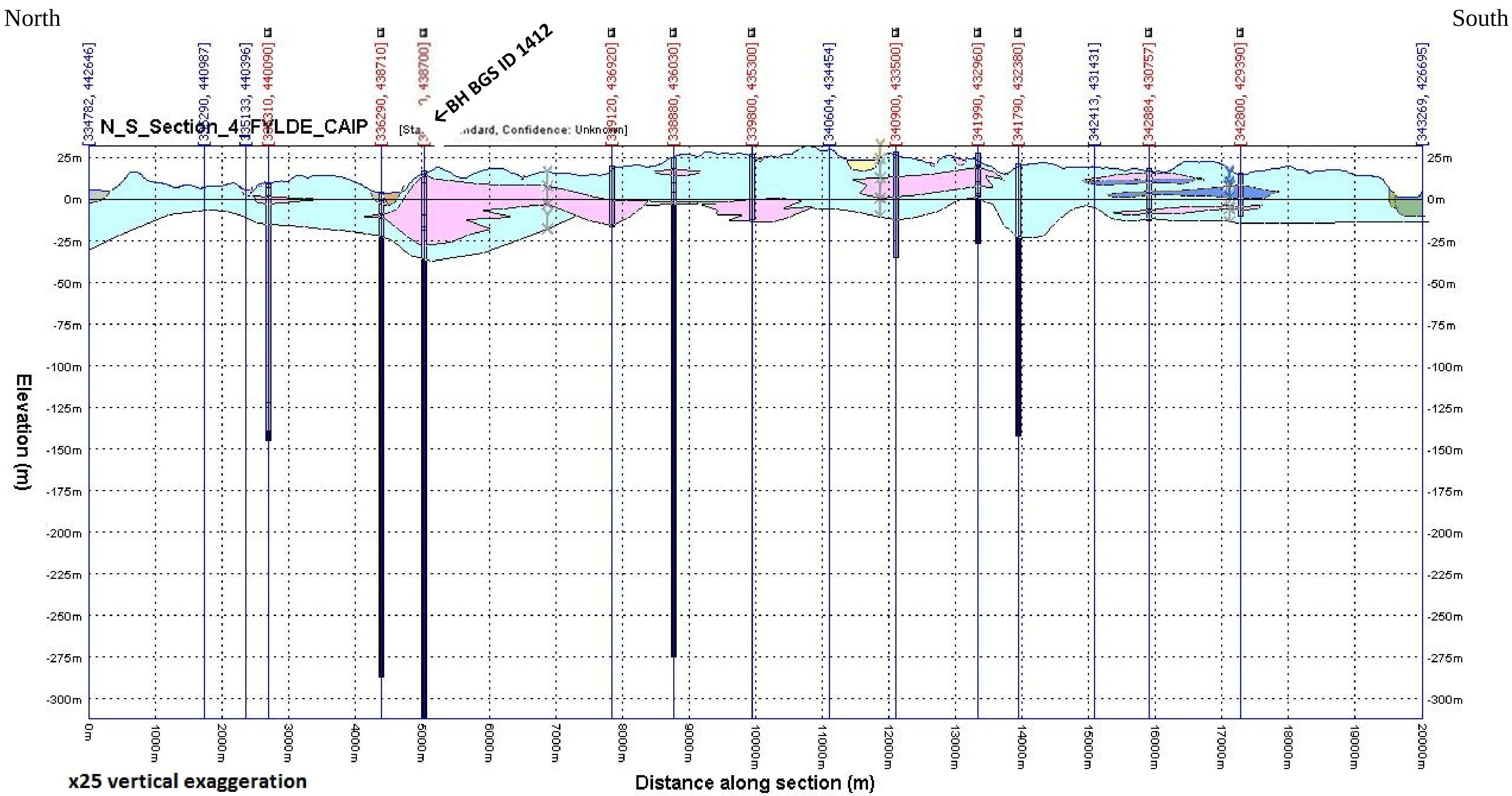
3.4.4.3 N_S_Section_3_Fylde_caip



The section starts at Stake Pool in the North, and runs south crossing the River Wyre and tributaries around Myerscough. It runs through Woodplumpton and reaches the shores of the River Ribble just outside of Preston. It is the most easterly of the north-south sections. The gridlines are 1km horizontal spacing and 25m vertical spacing.

The section shows various peat (brown) deposits at surface in the north of the area, and these rest on till (pale blue). This is accompanied by glacial deposits of glaciofluvial (pink) and till (pale blue) flanking and joining an area of bedrock high (the area beneath the yellow colour representing alluvium) in the middle of the section. To the south of the section, there is a thick succession of glaciofluvial deposits; this is shown in borehole BGS ID 4493. Interestingly, this borehole, as part of the glaciofluvial deposits, records a thick (20m) unit of boulders and coarse gravel.

3.4.4.4 N_S_SECTION_4_FYLDE_CAIP



This section runs from Thornton in the north, south through the outskirts of Poulton Le Fylde, and crosses the Fylde between the Roseacre and Preston New Road sites to Kirkham and reaches the banks of the river Ribble through Freckleton. The gridlines are 1km horizontal spacing and 25m vertical spacing.

The section shows a glacial succession of intercalated glaciofluvial units (pink) with till (pale blue). Borehole BGS ID 1412 shows there to be a thick 40m succession of glaciofluvial deposit, consisting of predominating of fine to coarse gravel. It is expected that the edges of the glaciofluvial deposits are irregular and intercalated with till deposits.

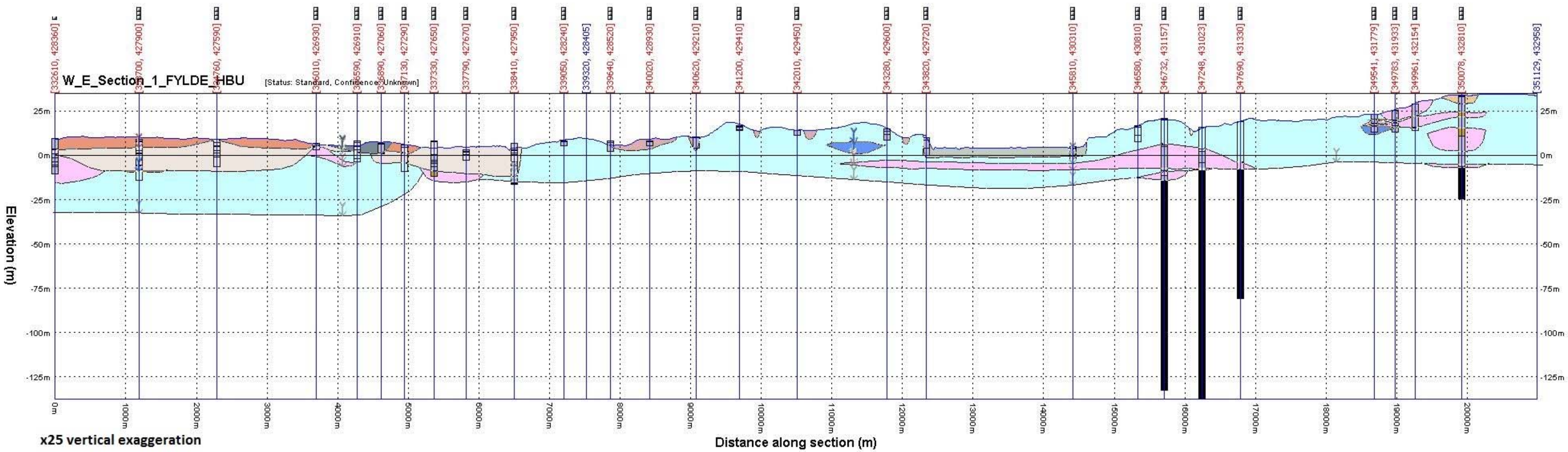
In the southern end of the section, there are several thin units of glaciolacustrine (dark blue) deposits, interbedded with till and glaciofluvial deposits.

Saltmarsh and tidal river (or creek) deposits are represented at the extreme south of the section as green units.

3.4.5 West-East sections

3.4.5.1 W_E_SECTION_1_FYLDE_HBU

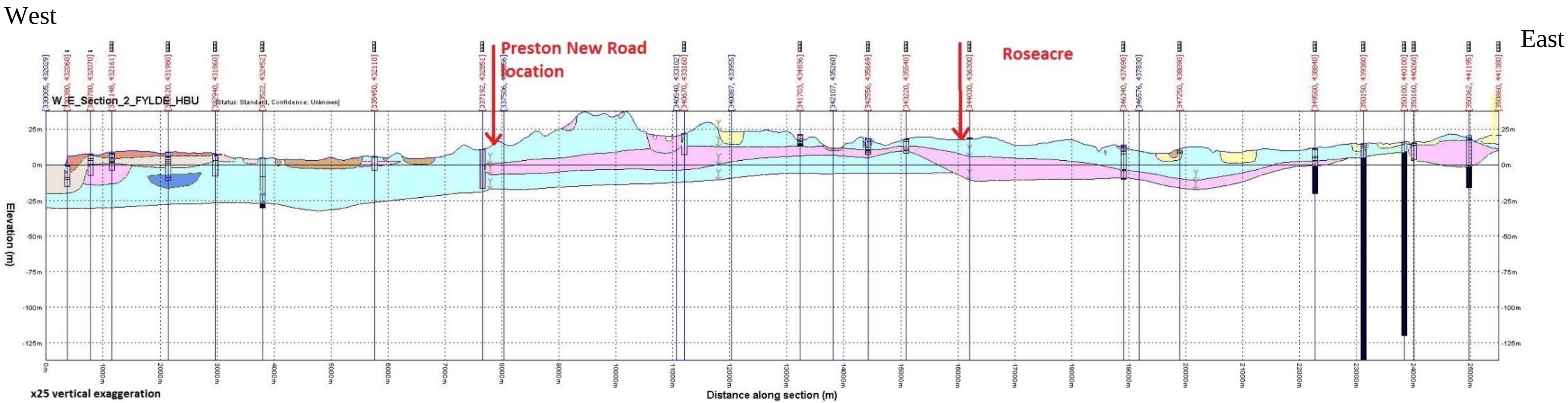
West East



Cross-section W_E_Section_1_FYLDE_HBU runs west to east in the south of the study area, from Lytham St Anne’s through to Preston. The gridlines are 1km horizontal spacing and 25m vertical spacing.

A consistent and relatively thick layer of till (pale blue) is modelled through the majority of the cross-section. However, there is no borehole evidence for till beneath the tidal flat deposits (yellow) and glacial sand and gravel (pink) at Saltcotes [337330, 427650] and till is therefore not modelled. The tidal flat deposits in this area are composed of clay, silt and sand. Several glaciofluvial sand and gravel lenses (pink) are modelled within the till in the east of the cross-section.

3.4.5.2 W_E_SECTION_2_FYLDE_HBU



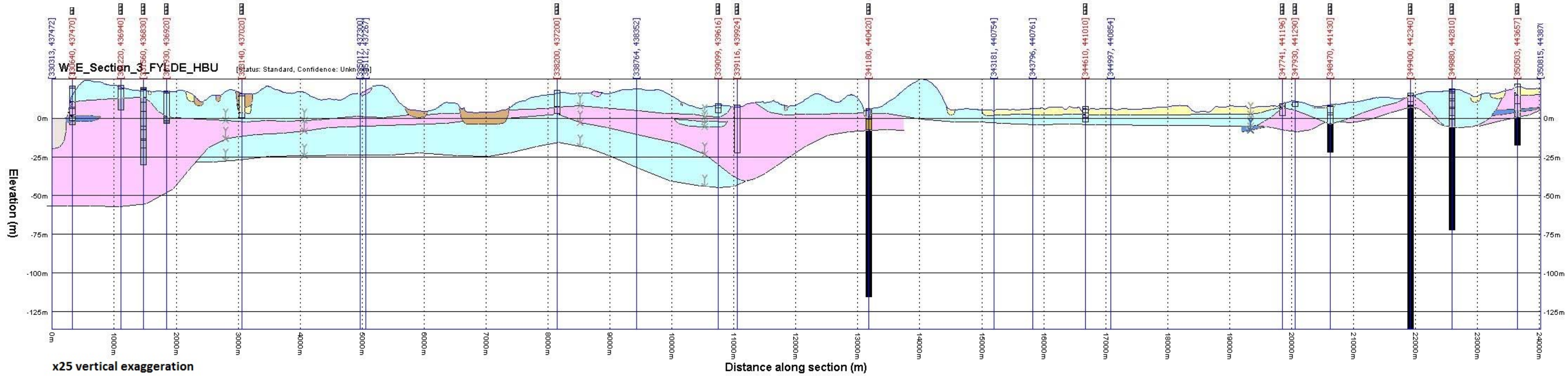
Cross-section W_E_Section_2_FYLDE_HBU runs west to east from Blackpool to Wesham, passing through the proposed test site at Preston New Road and, turning northeast through the Roseacre proposed test site to Stanzaker Hall Farm between Billborrow and Catterall. The gridlines are 1km horizontal spacing and 25m vertical spacing.

A consistent till layer (pale blue) is present through the majority of this section, with a persistent glacial sand and gravel unit (pink). The section cross-cuts the Kirkham Moraine between the sites of Preston New Road and Roseacre. It is present, however, across a broad tract of land going west-east across the southern Fylde. Addition details are given in Section 2 and Figure 8.

3.4.5.3 W_E_SECTION_3_FYLDE_HBU

West

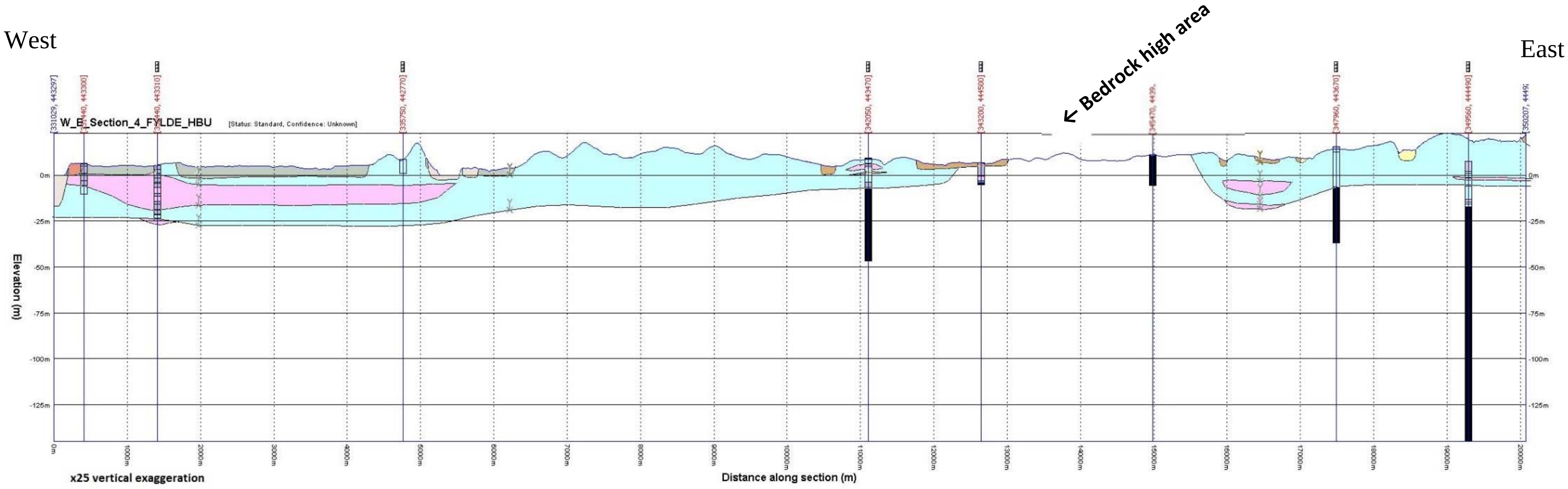
East



Cross-section W_E_Section_3_FYLDE_HBU runs from Blackpool and through Catterall in the north-east of the study area. The gridlines are 1km horizontal spacing and 25m vertical spacing.

Glacial sand and gravel rests on bedrock in the Blackpool area and is overlain by peat where the section crosses Main Dyke.

3.4.5.4 W_E_SECTION_4_FYLDE_HBU



Cross-section W_E_Section_4_FYLDE_HBU runs roughly west to east across the north of the study area, from Cleveleys, passing just north of Hambleton through to Bonds in the north-east corner of the study area. The gridlines are 1km horizontal spacing and 25m vertical spacing.

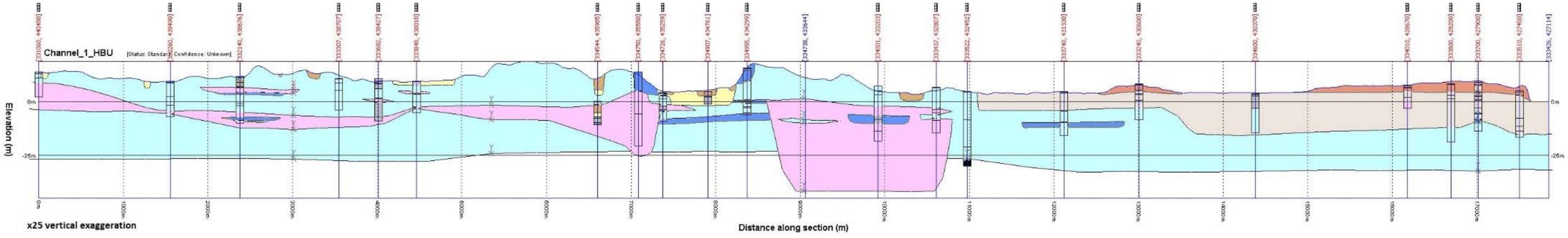
This cross-section shows a laterally persistent till unit (pale blue) with minor glacial sand and gravel (pink). A bedrock ‘high’ is proven in boreholes in the Manor House Farm area [345470, 443930].

3.4.6 Other sections

3.4.6.1 Channel_1_HBU

North

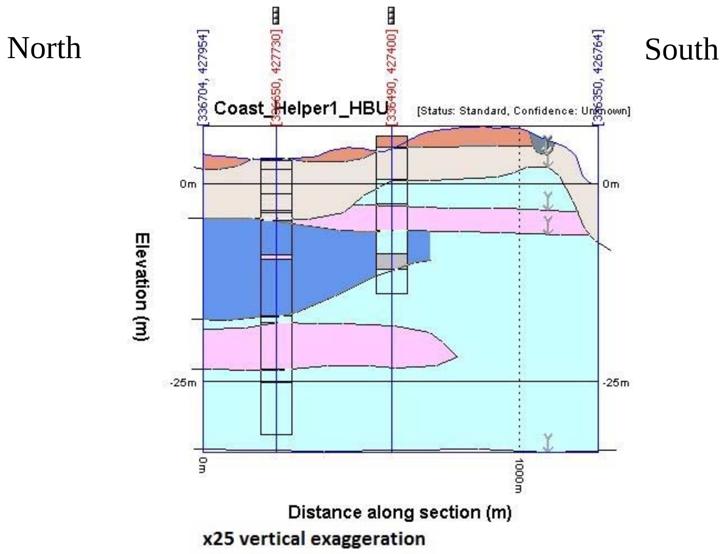
South



Cross-section Channel_1_HBU runs roughly north-south in the western part of the study area from the coast at Blackpool, passing just west of Staining, through southern Blackpool and Lytham Moss to Lytham St Anne's. The gridlines are 1km horizontal spacing and 25m vertical spacing.

This cross-section shows the complexity within the glacial sequence, with boreholes proving thick glacial sand and gravel deposits (pink) that intersect the till (pale blue). Thin layers of glaciolacustrine deposits (dark blue) are also present within the till. The overlying tidal flat deposits (yellow) are at their thickest in the Lytham St Anne's area.

3.4.6.2 Coast_helper1_hbu



Coast_Helper1_HBU is a short cross-section that runs roughly north-south through Lytham in the south of the study area. The gridlines are 1km horizontal spacing and 25m vertical spacing.

This cross-section was constructed using deep boreholes to help inform the thickness of superficial deposits in section W_E_Section_1_HBU in the absence of deep boreholes along the coast, although the boreholes do not reach rockhead. This cross-section shows a thick sequence of glacial deposits, dominated by till (pale blue), with layers of glacial sand and gravel (pink).

3.4.7 Fence diagram images

Figure 12 Fence diagram model image looking north

This shows the sections together in a fence diagram, looking northward. The till units (pale blue) can be clearly seen along with the glaciofluvial deposits (pink) and show how laterally extensive the glaciofluvial deposits could be across the Fylde model area. The tidal flat deposits (pale grey) can be seen in the extreme south west of the diagram, underlying the blown sand deposits (orange). The rest of the post-glacial deposits, however, are too thin/not laterally extensive enough to be seen on this image.

The location of the proposed test sites are marked in red. The south edge of the bounding box is approximately 22km in length.

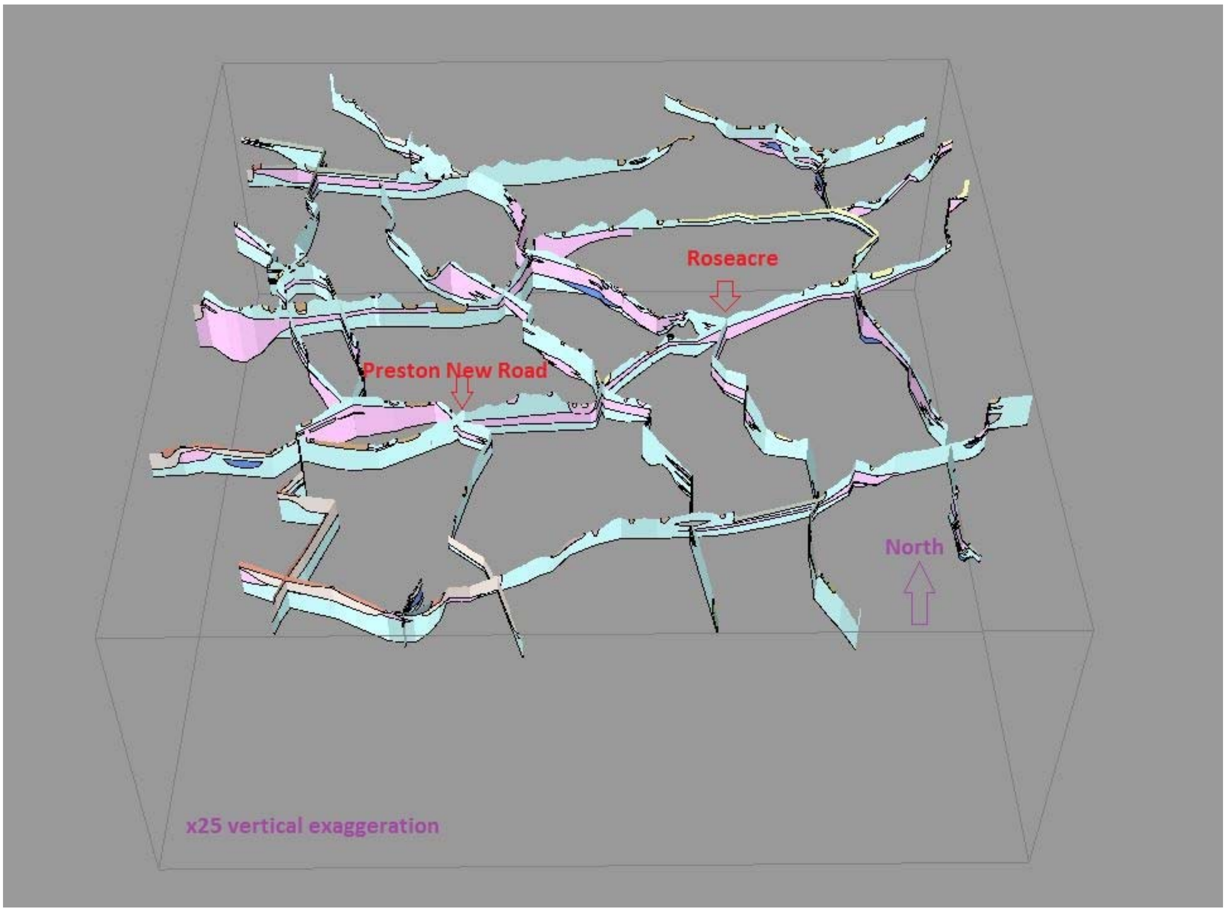
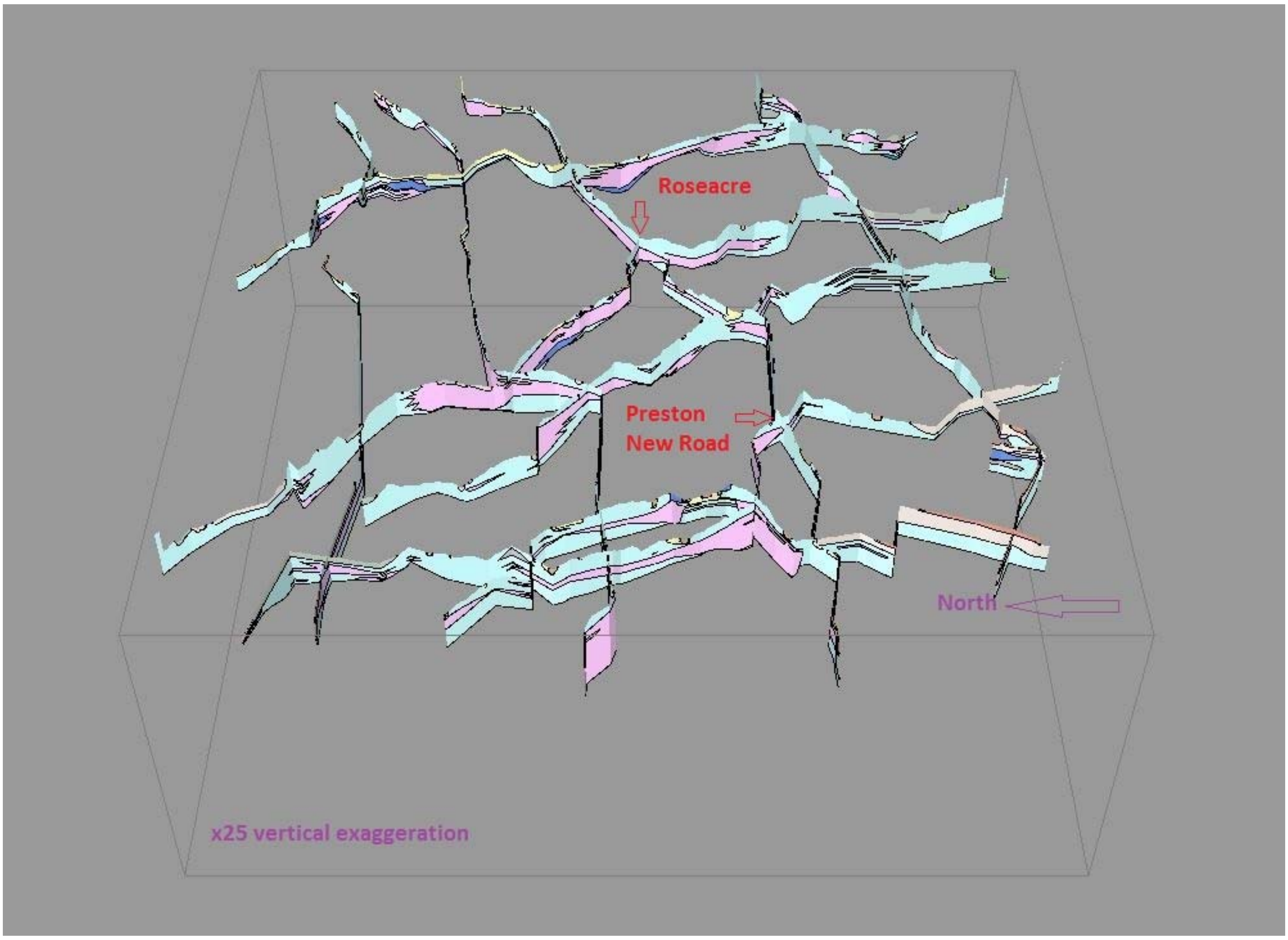


Figure 13 Fence diagram model image from the coast looking east

This shows the sections together in a fence diagram, looking eastward. The locations of the proposed test sites are marked in red. The south edge of the bounding box is approximately 22km in length.



3.5 RESULTS

3.5.1 Pre-Devensian landsurface

During the Devensian, a series of buried palaeochannels were incised into the bedrock surface, and subsequently infilled by a range of glacigenic deposits. Networks of buried valleys have been described from several areas in north-west England (e.g., Crofts et al., 2012; Howell, 1973), with the larger valleys having been mapped at a national scale (Lawley & Garcia-Bajo, 2009). A network of buried valleys within the south Fylde is suggested by the variable depth to bedrock in some areas and the irregular form of the rockhead surface. Often, this buried drainage pattern underlies modern drainage channels but significant areas of palaeo-drainage also exhibit no relation to modern drainage, for example, around the Staining area.

The modern bedrock surface has had numerous Quaternary geologic processes acting on it, and as a result of this, the bedrock has become weathered. Depending on the composition of the bedrock, the zone may be characterised by 'marls' on the Mercia Mudstone Group, and rock fragments and sands on the Sherwood Sandstone Group. The weathered zone may not be present across all bedrock surfaces.

Evidence of the weathered bedrock zone can be seen in boreholes that were used for this model, and summarised in Table 1. It can been seen that where proved by boreholes, the weathered bedrock zone is of variable thickness, in the region of 0.9-4.3m.

BGS_ID	DRILLED DEPTH TO BASE	THICKNESS OF WEATHERED ZONE	WEATHERED ZONE DESCRIPTION
4386	31.3m	4.3m	Soft, very broken, red brown very weathered fine grained sandstone with bands of harder thinly bedded sandstone
4493	45.72m	3.048m	Soft red sandstone with marl
4617	36.119m	0.457m	Red marl weathered Sherwood Sandstone Group
4838	11.278m	0.305m	Brown marly sandstone and gritty gravel
4840	21.336m	0.914m	Hard brown sandstone and some gravel and marl bands
4995	10.973m	0.915m	Red marl and sandstone

Table 1 Boreholes recording weathered rockhead

3.5.2 Devensian Glacial Sequence (i.e. the glacial deposits)

The cross-sections developed within the geological model broadly confirm the tripartite stratigraphy of the Devensian glacial succession for the region outlined previously (Wilson and Evans, 1990). This comprises a lower till, overlain by a middle unit of sands and an upper till unit, deposited within a single glacial episode. However, this crude tripartite sub-division masks the true lithological complexity of each of these units. For instance, both horizons of till contain discontinuous lenses of sand, sand and gravel, silt and clay. Similarly, the middle sand unit can be heterogeneous containing lenses of till, silt and clay.

The broad range and distribution of major and minor units suggests that numerous permeable horizons (sand and gravel) could exist enabling groundwater connectivity between the surface deposits and bedrock across much of the area; although a detailed understanding of the spatial continuity of individual units is limited by the density of available borehole data. Other potential pathways between strata include joints (natural fractures) which are common within most tills (Williams and Farvolden, 1967), with some sediment filled fractures extending into the bedrock (e.g., Wealthall et al., 2001; Hough et al., 2006). In addition, the pre-existing geology (i.e. glacial and uppermost bedrock units) is likely to be deformed by large-scale structures (folds and faults) especially in areas of ice-marginal thrusting (e.g. the Kirkham Moraine) and mass-wastage. Although not directly observed in the study area, these structural features are common within ice-marginal glacial landsystems elsewhere and could be encountered (Maizels, 1997; Thomas and Chiverrell, 2007; Benediktsson et al., 2008; Lee et al., 2013; Pedersen, 2014; Lee et al., 2015). Thus, the Devensian glacial sequence at a gross-scale, contains a dominantly sandy middle unit bounded above and below by clay till units albeit with complexity likely at a larger scale.

Locally, units of glaciolacustrine clay have accumulated, in ponded proglacial lake basins. These units are characterised by laminated silts and clays and would be expected to impede groundwater and subsurface fluid flow except where they contain interbedded sands.

Geological features including the lateral and vertical heterogeneity of glacial and post-glacial deposits and a highly complex regional drainage pattern indicate further complexity within the shallow sub-surface. This includes the surface distribution of glacial sand, sand and gravel, alluvium, peat and lacustrine deposits. Rather than form sheets, they generally form continuous linear ribbons (with modern superimposed drainage) or more discrete, discontinuous forms. Similar features have been mapped on Anglesey and were interpreted to be the product of: (1) post-glacial infill of small basins produced by mass-wastage of buried ice (e.g. kettle holes); (2) traces of former subglacial and / or proglacial drainage systems. The true geometry and continuity of these forms cannot be reconstructed within the sub-surface because of the limited borehole coverage. However, subglacial channels could potentially be several tens of metres deep, dissecting through the glacial sequence into the upper part of the bedrock succession. The occurrence of these features could give rise to complex fluid flow patterns.

3.5.3 Post-Glacial modification (i.e. post glacial deposits).

Following the retreat of the glaciers of the Devensian, the Fylde entered into a period of climate warming. Physical processes acted to deposit several units at the modern day land surface. These can broadly be divided into marine and coastal zone deposits, and terrestrial deposits (Table 2). In cross-section, they occur in a narrow zone at, and near, the present day land surface and are not generally as laterally extensive as the glacial deposits, which make up the bulk of material of the cross-sections. It is possible that there are intercalations of the different post-glacial units, particularly in the coastal zone, and along river valleys.

Terrestrial post-glacial deposits:	**Marine and coastal zone post-glacial deposits:**
Alluvium (clay, silt, sand and gravel) Peat (biogenic organic material) River Terrace Deposits (clay, silt sand and gravel) Head (clay, silt, sand and gravel)	Blown sand (sand) Storm Beach Deposits (sand and gravel) Raised Storm Beach Deposits (sand and gravel) Tidal River or Creek Deposits (clay and silt, sand) Salt Marsh Deposits (sand, silt and clay with organic debris)

Table 2 Summary of post-glacial deposits

Peat

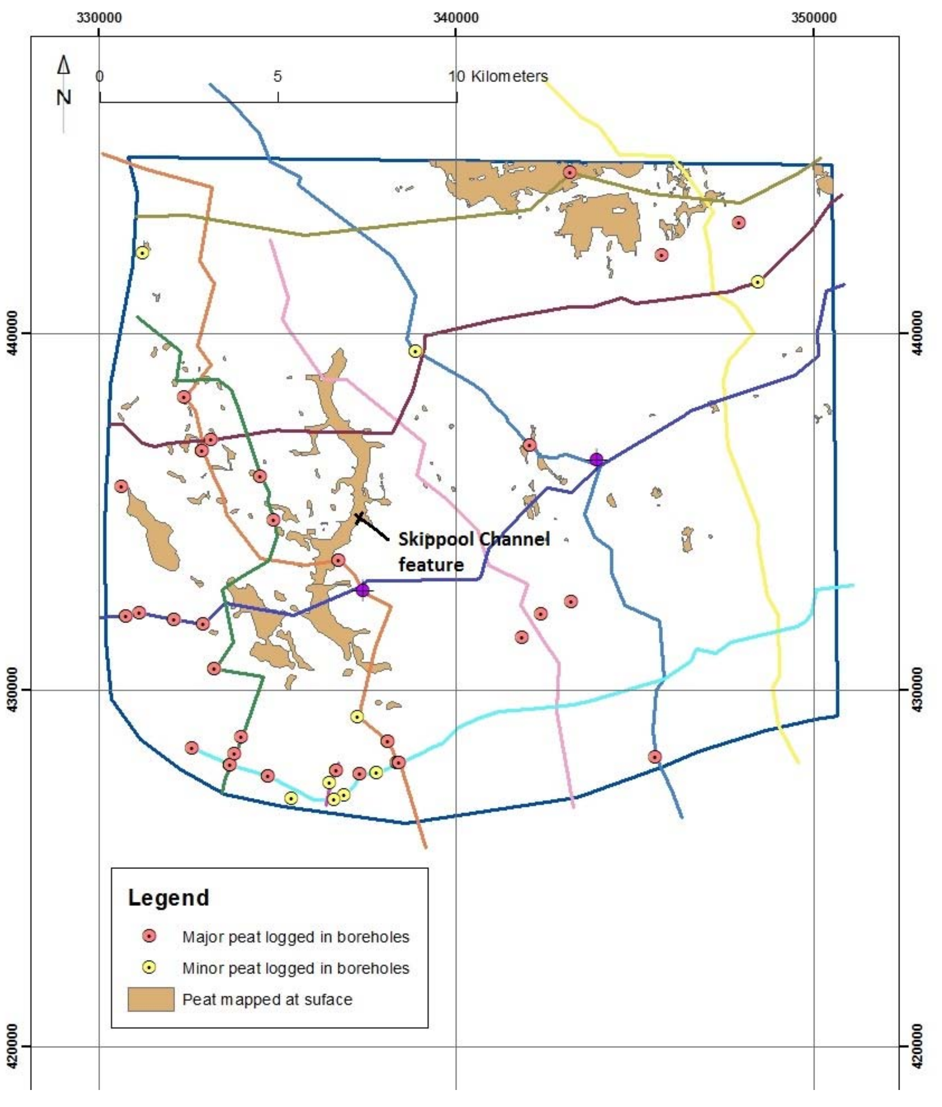
Peat (as biogenic organic material) occurs both in the subsurface and at surface within the Fylde (Figure 12 and Table 2). It occurs extensively as a primary deposit at surface in the 'Skippool Channel', a geological feature that runs in a north-south direction, in the western edge of the model area. The Skippool Channel is thought to have formed by glacial meltwaters in the Devensian (Wilson, 1990); however, its origin is contentious and poorly understood. The peat is likely to have accumulated in this feature due to its low-lying position and poorly draining substrate of clays and silts.

East of the River Wyre, there is another expanse of peat, in the north east of the model area. The peat would have been previously more extensive. The peat will have been removed for as a result of drainage, cutting and cultivation purposes, but also may have become desiccated and blown away.

In addition, unidentified lenses of peat may be present throughout the model area. These are been seen scattered at surface throughout the model area, but particularly in the south-east. It is thought that these accumulated in small kettle holes left following the retreat of the Devensian glaciers.

In the subsurface, an expanse of peat lies along the coast from South Shore, Blackpool to Lytham St Anne's, and inland eastward outcropping around Marton Moss at surface. It lies underneath the blown sand deposits and can be seen in cuttings along the coast. In addition, it contains the decayed remains of trunks of trees identified as oak, alder, yew, ash and fir (Wilson, 1990). It is likely to be the oldest peat in the model area. Figure 14 shows this peat as red boreholes with no surface peat associated with them in the Blackpool and Lytham St Anne's area. The peat layer reaches 2-3m thick.

Figure 14 Map showing the surface and borehole distribution of Peat in the Fylde area



3.6 CHARACTERISING THE REGIONAL SUPERFICIAL GEOLOGY AROUND THE PROPOSED TEST SITES

The Quaternary sediments at Roseacre are expected to be approximately 28-30m deep and at Preston New Road 30-32m. There is the potential for a weathered bedrock zone, up to 5m thick, which may contain uncemented material. The fence diagram model shows that at both sites, the superficial Quaternary succession is expected to be composed of glacial till (gravel in a clay matrix) and glaciofluvial deposits (free running sands and gravels). In the absence of site-specific data, the precise lithological composition of the units and their lateral extent is not known. The glaciofluvial succession could potentially be a host to fluid flow, as it typically comprises unconsolidated sand and gravels. In contrast, the glacial till could potentially impede fluid flow, due to the predominance of the clay matrix, although fracture flow may be possible through any joints present. However, there will be marked facies variations within both these units which may locally enhance or reduce flow pathways within these deposits.

4 Summary and conclusions

This study was undertaken as part of a NERC environmental baseline monitoring programme around the potential hydraulic fracking sites in the Fylde region, Western Lancashire. A regional superficial (i.e. Quaternary) fence diagram was been generated based upon existing geological maps and borehole records.

It is shown that the superficial cover in the Fylde region is absent in the bedrock high area, to over 50-60m thick in areas where there may be buried channels or other palaeorelief features. On average, however, the superficial cover is estimated to be 30-40m thick across the Fylde area. This estimation includes a weathered bedrock zone up to 5m thick.

A rockhead high (where bedrock is very close to the surface) was identified around Rawcliffe Moss (show on Section W_E_4_Fylde_HBU), to the west of Catterall, in the north east of the model area.

The glacial deposits comprise tills (gravels in clay matrix), glaciofluvial deposits (free running sands and gravels), and glaciolacustrine deposits (laminated silts and clays) in varying proportions. The glaciofluvial deposits could potentially provide flow pathways that could be very laterally extensive and behave in an unpredictable way. In addition, they may connect hydraulically to the underlying bedrock. The clays of the tills and glaciolacustrine units could provide a barrier to fluid flow.

Post-glacial deposits are not as extensive or thick as the glacial deposits and are characterised by marine and coastal zone deposits and terrestrial deposits.

Coastal zone deposits include tidal flat deposits (grey silts and clays), storm beach deposits (silts, sands and gravels), blown sand (sands), tidal river or creek (clays, silts and fine sands) and saltmarsh deposits (sands, silt and clay with organic debris).

Post glacial terrestrial deposits include alluvium (clays, silts, sands and gravels), peat biogenic organic material) and head (clay, silt, sand and gravels).

The superficial deposits, particularly within the glacial units, show a very strong lateral and horizontal variability. This is due to the varying character of the depositional environments and physical processes depositing the sediments, and also post-depositional processes, such as shearing of the sediment pile beneath an oscillating ice-margin. In areas away from further from boreholes with lithological logs, there is increasing uncertainty in the distribution of the modelled units.

Appendix 1

Below is a list of all the non-confidential boreholes that were used in the model.

LIST OF BOREHOLES

BGS_ID	EASTING	NORTHING	Scan_Link
1216	338340	427970	http://bgsintranet/scripts/ida/boreholescan/dispBorehole.cfm?bgsID=1216
1322	339050	428240	
1233	337130	427290	http://bgsintranet/scripts/ida/boreholescan/dispBorehole.cfm?bgsID=1233
15636501	336890	427060	
1258	336650	427730	http://bgsintranet/scripts/ida/boreholescan/dispBorehole.cfm?bgsID=1258
1274	338410	427950	
1278	337260	429260	
1225	336590	426910	http://bgsintranet/scripts/ida/boreholescan/dispBorehole.cfm?bgsID=1225
1283	338090	428560	
1226	336490	427400	http://bgsintranet/scripts/ida/boreholescan/dispBorehole.cfm?bgsID=1226
1300	335210	427040	
1301	335400	426970	
1227	337330	427650	http://bgsintranet/scripts/ida/boreholescan/dispBorehole.cfm?bgsID=1227
1304	336010	426930	
1314	337790	427670	
1318	339640	428520	
1364	333800	428200	http://bgsintranet/scripts/ida/boreholescan/dispBorehole.cfm?bgsID=1364
1331	333700	427900	http://bgsintranet/scripts/ida/boreholescan/dispBorehole.cfm?bgsID=1331
1371	334040	427460	
1374	334640	427270	
1377	332610	428360	http://bgsintranet/scripts/ida/boreholescan/dispBorehole.cfm?bgsID=1377
1383	334010	428670	http://bgsintranet/scripts/ida/boreholescan/dispBorehole.cfm?bgsID=1383
1333	334760	427590	http://bgsintranet/scripts/ida/boreholescan/dispBorehole.cfm?bgsID=1333
12724200	333510	427450	
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