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A Conceptual Geological Model for investigating shallow sub-surface geology, Cheshire Energy Research Field Site

Geology and Regional Geophysics Programme

Open Report OR/17/042

BRITISH GEOLOGICAL SURVEY

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A Conceptual Geological Model for investigating shallow sub-surface geology, Cheshire Energy Research Field Site

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Foreword

New and emerging subsurface energy technologies and the extent to which they might make a major contribution to the energy security of the UK, the UK economy and to jobs is a subject of close debate. There is a need to better understand the impacts of energy technologies on the subsurface environment. The British Geological Survey vision is that the research facilities at the UK Geoenergy Observatories will allow ground-breaking scientific monitoring, observation and experimentation to gather critical evidence on the impact on the environment (primarily in terms of the sub-surface and linking to the wider environment) of a range of geoenergy technologies.

The Natural Environment Research Council (NERC) through the British Geological Survey, in collaboration with the UK environmental science-base and industry, will deliver the UK Geoenergy Observatories project comprised of two new world-class subsurface research facilities. These facilities will enable rigorous, transparent and replicable observations of subsurface processes, framed by the UK Geoenergy Observatories Science Plan[1]. The two facilities will form the heart of a wider distributed network of sensors and instrumented boreholes for monitoring the subsurface across the UK. Scientific research will generate knowledge applicable to a wide range of energy technologies including: shallow geothermal energy, shale gas, underground gas storage, coal bed methane, underground coal gasification, and carbon capture and storage.

The UK Geoenergy Observatories project will create a first-of-its-kind set of national infrastructure research and testing facilities capable of investigating the feasibility of innovative unconventional and emerging energy technologies. Specifically, the project will allow us to:

- deploy sensors and monitoring equipment to enable world-class science and understanding of subsurface processes and interactions;
- develop real-time, independent data capable of providing independent evidence to better inform decisions relating to unconventional, emerging and innovative energy technologies policy, regulatory practice and business operations in these technology areas.

This report is a published product of the UK Geoenergy Observatories project (formerly known as the ESIOS project), by the British Geological Survey (BGS) and forms part of the geological characterisation of the Cheshire site. The report gives a conceptual overview of the shallow sub-surface geology around the Cheshire Energy Research Field Site, including a review of geological processes that have been active in this vicinity following the deposition of the youngest preserved bedrock in the area, the Sherwood Sandstone Group. This recent geological history has resulted in a complicated near-surface succession that influences the properties of rocks and soils. These have an effect on sub-surface flow processes and behaviour.

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[1] UK Geoenergy Observatories Science Plan: download here.

Contents

Figure and Table Captions

FIGURE CAPTIONS

Figure 2.1. A workflow for the conceptual 'systems' geological approach. Effectively, by taking two known components it is possible to predict the third unknown component.

Figure 3.1. Location of the Cheshire Energy Research Field Site (green dot) adjacent to the River Mersey in Cheshire. Includes Ordnance Survey data © Crown copyright and database rights [2017] Ordnance Survey [100021290 EUL].

Figure 3.2. The bedrock geology of the Cheshire Basin (CB) showing the distribution of major bedrock units (DigMAP625) and faulting (dashed lines). Orange (Permian) and light pink (Triassic): Sherwood Sandstone Group; Dark pink (Triassic): Mercia Mudstone Group. NEXTMap Britain elevation data from Intermap Technologies.

Figure 3.3. The burial and exhumation history of the top of the Sherwood Sandstone Group based upon vitrinite reflectance (VR) data from three sites in NW England (DECC, 2013).

Figure 3.4. Evolution of Cenozoic climate with specific references to major tectonic (brown) and climatic (blue/red) global events (Modified from Newell, 2014). Oxygen isotope data from Zachos *et al*. (2008). Abbreviations: PETM – Palaeocene-Eocene Thermal Maximum; EECO – Early Eocene Climatic Optima; MECO – Mid Eocene Climatic Optima; MMCO – Mid Miocene Climatic Optima.

Figure 3.5. The extent and dynamics of the Last British-Irish Ice Sheet during the Late Devensian glaciation (after Clark *et al*., 2012). The thick solid and dotted line corresponds to the maximum known ice extent (non-synchronous). The Cheshire Energy Research Field Site is indicated by the red square.

Figure 3.6. The superficial geology of the Cheshire Basin (CB) showing the distribution of major units (DigMAP50). Blue: Late Devensian till; Pink: Late Devensian glaciofluvial deposits; Orange: river terrace deposits; Yellow: Holocene coastal deposits. NEXTMap Britain elevation data from Intermap Technologies.

Figure 4.1. A rockhead (geological) relief model for the northern Cheshire Basin including the study site (green dot). Pale yellow and pale green areas of shading correspond to areas of lowest rockhead relief and, where connected, the location of major buried valleys. Includes Ordnance Survey data © Crown copyright and database rights [2017] Ordnance Survey [100021290 EUL].

Figure 4.2. Rockhead (geological) surface model adjacent to Cheshire Energy Research Field Site (green dot) showing a major buried valley (pale yellow to pale green) to the west extending northwards to Ellesmere Port joining an assumed valley that extends beneath the Mersey Estuary. Borehole locations are indicated by small black dots. Includes Ordnance Survey data © Crown copyright and database rights [2017] Ordnance Survey [100021290 EUL].

Figure 4.3. A coastal section through Irish Sea-derived till from Anglesey, north Wales.

Figure 4.4. An example of a heavily-fractured till, east Yorkshire, showing vertical and horizontal joint sets.

Figure 4.5. Structural interpretation of deformed bedrock and superficial sequences at Møens Klint, Denmark (from Lee and Phillips, 2013).

Figure 4.6. A schematic model (not to scale) showing the predicted natural superficial geology beneath the search area. The ground surface slopes from south to north.

TABLE CAPTIONS

Executive Summary

This report provides a conceptual overview of the shallow sub-surface geology around the Cheshire Energy Research Field Site. The report assumes that the reader has a basic level of geological understanding and therefore it employs geological terminology throughout although terms are explained where appropriate. The Executive Summary provides an overview of the report for the non-geologist.

The report describes the natural geological processes that have occurred since the deposition of the youngest bedrock units (Sherwood Sandstone Group, SSG), how these have shaped the landscape and sub-surface geology and the likelihood of unpredictable geological features that may influence ground conditions. The report does not consider the impact of human activity, emplacement of fill or land development in the area. Since the deposition of the SSG about 200 million years ago, the area has undergone marked geological change. It has resulted in the deep burial of the SSG to depths of at least several kilometres followed by progressive uplift (and erosion of overlying rocks) to the land surface. The SSG has been exposed at the land surface for much of the last five million years (probably much longer), resulting in prolonged periods of weathering under a range of different climatic (temperate and arctic) regimes forming an intensely weathered zone (called a ‘saprolite’) of variable thickness (up to about 40 metres) that mantles the bedrock. An additional influence on the SSG is the likely cyclical incursion and flushing of saline groundwater during fluctuating sea level over the past two and a half million years. The flushing of fresh glacial meltwaters during glacial intervals is also a process that will have influenced the pore-water chemistry to depths of a few hundreds of metres from surface. Collectively, these weathering processes have acted to alter the physical and chemical properties of the SSG. This can make distinguishing between weathered and unweathered SSG and natural superficial deposits (some of which are largely derived from the SSG) very challenging without detailed analyses.

Over the past two million years, the bedrock surface has also been sculpted by glaciers, rivers and coastal processes forming a highly-irregular surface which is dissected by buried channels that have no surface expression within the modern landscape. Due to the sparse distribution of data points proving rockhead, the geometry and extent of these hidden channels is generally poorly-constrained but where present they typically generate windows of enhanced hydraulic conductivity within the shallow sub-surface (locally up to depths of 40 – 50 m). The sandstone and weathered bedrock is believed to have been largely buried beneath a veneer (metre to tens-of-metres thick) of sediment laid-down during glaciation and to a lesser extent by coastal, river and anthropogenic processes. Where the substrate has been overridden by glaciers, these sediments may have been folded, fractured or displaced. These sediments are likely to be highly-variable in terms of their composition, geometry, structure and properties creating highly-localised zones of preferred groundwater flow and complex ground conditions.

In summary, the properties of the shallow geological strata near the Cheshire Energy Research Field Site are predicted to be highly-complex. Our understanding of the geological processes that have affected the region since the deposition of the SSG provide important clues as to what these complexities may be but not where they may occur. This can only be resolved by further detailed geological investigations.

1 Introduction

This report provides an overview of the natural near-surface geology of the Cheshire Energy Research Field Site, located between Stanlow and Ince Marshes, to the east of Ellesmere Port. It adopts a conceptual predictive approach to reconstruct a geological model for the site based upon the range of geological processes and environments that are known to have operated in Britain and the northern Cheshire over recent geological time. The report describes the conceptual approach adopted before outlining the geological history of the area. Finally, an overview of the geological processes that have affected the Ince Marshes area is outlined and the likely occurrence of related geological features presented. The report assumes that the reader has a basic level of geological understanding so whilst the terminology employed is by necessity 'technical', terms and basic concepts are explained where appropriate. A non-technical overview of this report is provided by the Executive Summary.

For a detailed account of the Quaternary geology at the Cheshire Energy Research Field Site and surroundings, please refer to Burke *et al*. (2016).

2 Methodology

2.1 CONCEPTUAL GEOLOGICAL MODELS

Geological understanding of any area is underpinned principally by the quality, type and quantity of geological data that is available. Within many flat, low-lying coastal areas such as Ince Marshes, natural exposures of the geology are often limited. Geologists therefore rely upon borehole records (where available), non-invasive techniques (e.g. geophysics), site investigation records and observed changes in soil texture and composition to infer the underlying geology. An alternative approach is the Conceptual Geological Model (Figure 2.1) which utilises a semi-iterative approach routinely employed by geologists to build a hierarchical level of observational, interpretational and contextual knowledge and resolve a specific geological problem (Eyles, 1983; Evans, 2003; Rose, 2010; Booth *et al*., 2015). This approach is very similar to a 'conceptual ground (or site) model', which is a conceptual tool employed by civil engineers and hydrogeologists to support decision-making and ground investigation. However, within this context, the Conceptual Geological Model adopts a systems approach to explain the range of 'geological products' (e.g. sediments, structures, landforms and volumes) that may be anticipated relative to the known (and assumed) geological history of a site or area. In other words, by understanding the 'geological drivers' and how these have evolved in time and space, it is possible to predict many of the 'geological processes' that operated within the landscape and, in-turn, the 'geological products' that may be present (i.e. the properties and characteristics of the geological record). Ultimately, this process relies upon one (or ideally two for increased confidence) components of the workflow to be understood to infer to the third.

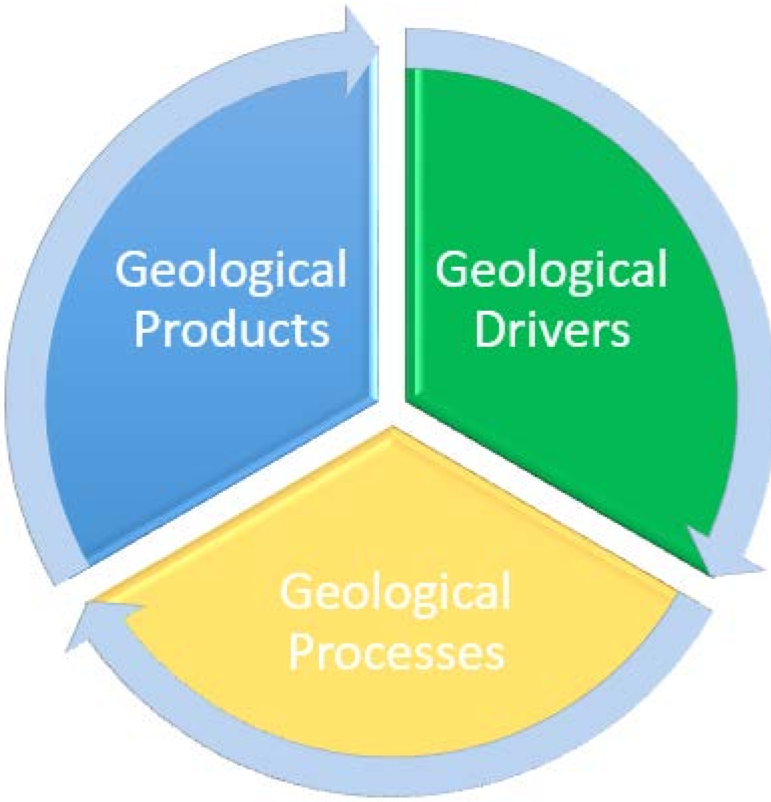


Figure 2.1. A workflow for the conceptual 'systems' geological approach. Effectively, by taking two known components it is possible to predict the third unknown component.

Understanding the drivers and processes of landscape evolution and, in-turn, how they have evolved in time and space, is crucial for developing a robust conceptual geological model that outlines the range of properties that may be present within the shallow sub-surface. The range of geological drivers and processes that have operated within the landscape since the youngest bedrock units were deposited may have changed due to natural changes in geography, climate and tectonic stress regime. However, going back in geological time, our ability to visualise and interpret the geological record going back in geological time typically declines. This reflects the reduced resolution and preservation of the geological record with age; a reduced ability to qualify (and quantify) rates of change; and finally, a more limited understanding of the geological context compared to modern day.

In terms of the study area and northern part of the Cheshire Basin, the youngest bedrock geology encompasses Triassic-age sandstones and mudstones, overlain unconformably by superficial deposits of variable thickness and composition. The absence of rocks or sediments of intervening age (c.200 Ma) means that evidence for the area's geological history during this time is sparse and this limits the direct observations and inferences that can be made. Nevertheless, by analogy with the wider geological evolution of NW England and the East Irish Sea Basin, it is possible to make assumptions about the broader geological history of the study area, which can inform this study.

This report focusses on geological processes that have acted on bedrock, and the resulting Quaternary sediments, from the Late Devensian (27 ka) onwards. However, processes pre-dating this time will have had a significant impact on the local Permo-Triassic bedrock (Sherwood Sandstone Group). These processes have influenced the generation and character of fractures and joints within the Sherwood Sandstone, and the development and evolution of cements through post-depositional diagenetic processes. Further details are in Strong *et al*. (1994) and Milodowski *et al*. (1999) (and references therein), which are summarised below.

Strong *et al.* (1994) describe the petrology and diagenesis of the Permo-Triassic strata near Sellafield in Cumbria' approximately 125 km to the north of the Cheshire Energy Research Field Site. They note that the diagenesis of the St Bees Sandstone (laterally equivalent to the Sherwood Sandstone Group in Cheshire) is characterised by non-ferroan dolomite, quartz, ferroan and non-ferroan calcite and late illite. Analysis indicates that porosity is secondary, following the influence of modern groundwater action, but also the early removal of evaporate cements allowed for the preservation of early-stage porous fabrics.

Milodowski *et al.,* (in Plant *et al.*, 1999) conducted a study of the diagenetic history and processes relevant to sandstone-hosted mineralisation in the Sherwood Sandstone Group in the Cheshire Basin and Wirral Peninsular. They proposed a diagenetic paragenesis for the group and related this to the burial history of the Cheshire Basin. They identify eight main phases of diagenesis, ranging from shallow diagenesis/pedogenesis immediately following deposition, to telodiagenetic alteration influenced by modern near-surface groundwaters.

2.2 MEASURING UNCERTAINTY

Measuring *uncertainty* or the *likehood of occurrence* is a fundamental component of communicating geospatial data. Within the context of this report, uncertainty is used to communicate the likehood that a particular geological feature will be present beneath the Ince Marshes study area. Various methodologies have been published that communicate levels of uncertainty although these are principally quantitative (e.g. Kandlikar *et al*., 2005; Patt and Dessai, 2005; Ellingwood and Kinali, 2009; Mastrandrea *et al*., 2010). However, for the purpose of this study, a qualitative approach to uncertainty is employed and the terminology outlined below in Table 2.1.

Term	**Likelihood of Occurrence**
Virtually certain	Virtually certain to occur other than in exceptional circumstances.
Very likely	Much more likely to occur than not.
Likely	More likely to occur than not.
About as likely as not	May or may not occur.
Unlikely	More unlikely to occur than likely to occur.
Very unlikely	Much more unlikely to occur that likely to occur.
Exceptionally unlikely	Unlikely to occur other than in exceptional circumstances.

Table 2.1. Communicating levels of uncertainty / likelihood of occurrence.

3 Context of Study Area

3.1 LOCATION OF STUDY AREA

The study site, approximately 0.5 km^2, is the Cheshire Energy Research Field Site located between Stanlow and Ince Marshes, Cheshire. Situated adjacent to the Mersey Estuary, the Cheshire Energy Research Field Site is located east of Ellesmere Port and approximately 8.5 km to the northeast of Chester (Figure 3.1). It is bounded to the north by the Manchester Ship Canal that runs broadly east-west parallel to the shoreline of the Mersey Estuary, and to the south and west by the M56 and M53 motorways respectively. The area is low-lying, sloping gently northwards towards the Mersey Estuary and dissected by several drains and streams. The natural surface elevation around Ince Marshes lies between approximately 5-8 metres OD. However, coastal land-reclamation and flood protection measures constructed during the development of a nearby oil refinery and on-site industrial units mean that the current and / or localised elevation of the land-surface may be markedly higher.

Figure 3.1. Location of the Cheshire Energy Research Field Site (green dot) adjacent to the River Mersey in Cheshire. Includes Ordnance Survey data © Crown copyright and database rights [2017] Ordnance Survey [100021290 EUL].

3.2 GEOLOGICAL OVERVIEW: DRIVERS OF LANDSCAPE EVOLUTION

Within this section of the report, a regional overview of the long-term geological history of the broader Cheshire region is given, focussing on the geological drivers and where appropriate, the known geological processes and geological products.

The area around Ince Marshes lies within a major area of Quaternary erosion and deposition, which itself, is superimposed upon a Late Palaeozoic to Mesozoic basin known as the Cheshire Basin. The basin extends from Manchester in the north to Shropshire in the south and is bound by several large broadly north-south striking extensional (normal) fault systems that separate the basin from adjacent strata (Carboniferous and older) to the west and east. Formation of the basin began in response to crustal extension during the Permian, which also affected other parts of the West Midlands and the neighbouring Irish Sea (Newell, 2017). The occurrence of additional extensional faults within the Cheshire Basin (CB) also demonstrate that basin subsidence did not occur *en bloc* but discretely through differential movement of faulted basinal blocks - presumably exerting a significant influence locally on sedimentation during the Permian and Triassic.

The geological infill of the Cheshire Basin comprises Triassic age sandstones (Sherwood Sandstone Group, SSG) and mudstones (Mercia Mudstone Group, MMG) (Figure 3.2; Ambrose *et al.*, 2014). Beneath Ince Marshes, the bedrock geology is composed entirely of the SSG, a siliciclastic sandstone of Early to Mid-Triassic age (c.251-240 Ma) that dips gently (c. 5^o) to the south-east. Permo-Triassic rocks extend offshore into the East Irish Sea Basin (EISB) where up to 1,160 m of SSG is preserved (British Geological Survey, 2012). Due to the paucity of age-diagnostic fossils, the SSG cannot be sub-divided biostratigraphically and in-turn chronostratigraphically. Instead, strata are classified lithostratigraphically with sub-division into lithofacies according to their primary (e.g. lithology and sedimentology) and secondary (e.g. colour and diagenesis) sedimentological properties. Examining and describing available bedrock exposures and borehole cores is therefore central to sub-division of the SSG. Two main lithofacies associations have to-date been recognised. Firstly, *fluvial facies* which correspond to the Chester, the upper part of the Wilmslow and parts of the Helsby formations and comprise single or multi-storey sand bodies comprising thick, upward-fining sets of sandstone with erosional-based, cross-bedded lower horizons. Where stratified, sandstone facies exhibit planar, low and high-angle cross-bedding, planar- and ripple-lamination indicating fluctuations in flow regime. Rip-up clasts are common within the lower parts of some sets and are composed of host (intraformational) or derived (extraformational) lithologies. Over-steepened bedding and water-escape structures are described in exposures at Runcorn (Mountney and Thompson, 2002) and the Wirral (Benton *et al.,* 2002). Similar sedimentary structures have been observed near Blackpool and are interpreted as the product of syn-depositional earthquakes (Wilson and Evans, 1990). Alternatively, these types of structures could simply be the product of rapid syn-depositional loading of water-saturated strata (cf. Reineck & Singh, 1980). Secondly, an *aeolian facies* (the predominant facies of the Wilmslow Formation, and developed in parts of the Helsby Formation), is described from equivalent units elsewhere in northwest England (e.g. Thompson, 1970; Macchi, 1991; Howard *et al.,* 2007). This facies is composed of well-sorted sandstones with rounded medium- to coarse-grained frosted quartz-rich sand with well-developed 'pinstripe' cross-lamination and large-scale planar cross-bedding. The grain size distribution, maturity, grain frosting and sedimentary structures are characteristic of sedimentation as part of mobile sand dune fields.

A major regional unconformity exists between Triassic and Quaternary strata in the Cheshire Basin, extending north and westwards into the EISB (Jackson *et al.*, 1995). Rocks of intervening

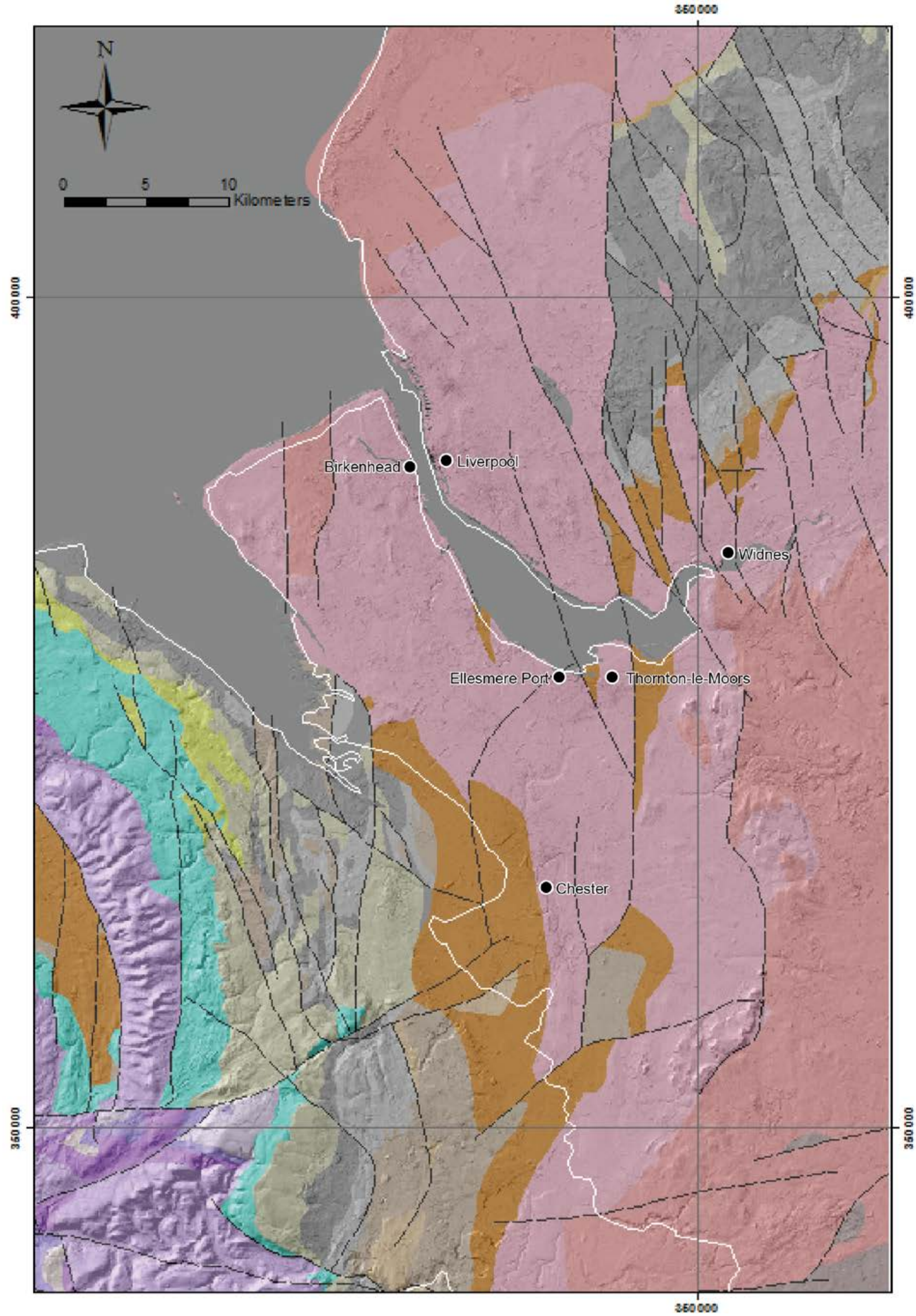


Figure 3.2. The bedrock geology of the Cheshire Basin (CB) showing the distribution of major bedrock units (Digital geological map data BGS © NERC; contains Ordnance Survey data © Crown Copyright and database rights 2017.) and faulting (dashed lines). Orange (Permian) and light pink (Triassic): Sherwood Sandstone Group; Dark pink (Triassic): Mercia Mudstone Group. NEXTMap Britain elevation data from Intermap Technologies.

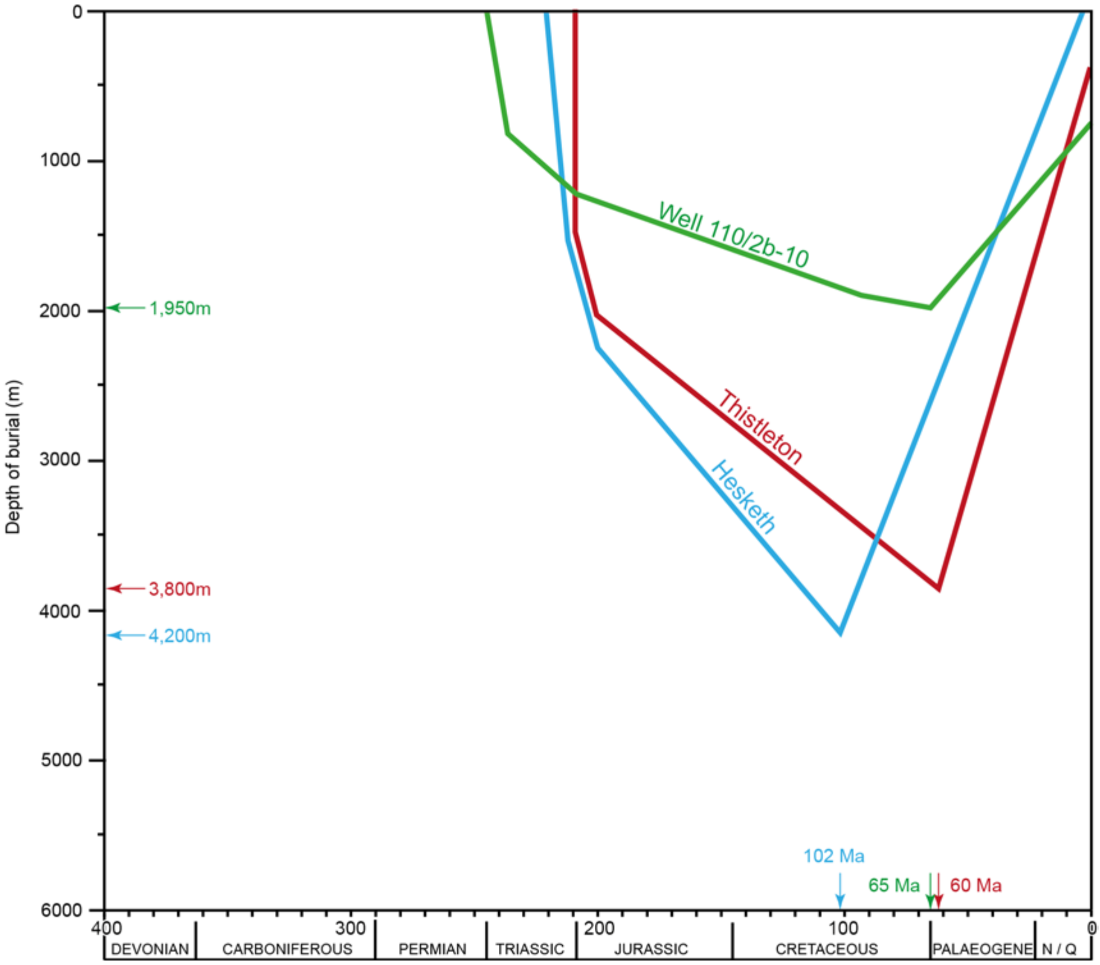
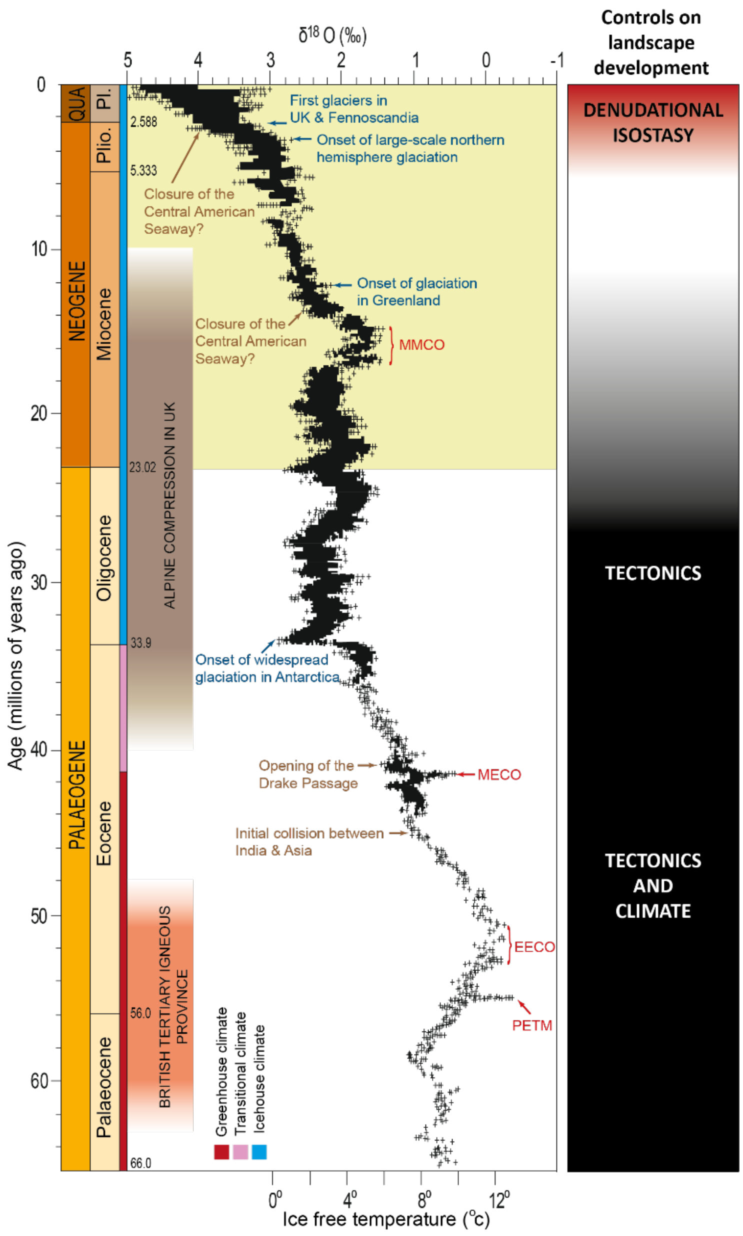


Figure 3.3. The burial and exhumation history of the top of the Sherwood Sandstone Group based upon vitrinite reflectance (VR) data from three sites in NW England (DECC, 2013).

age (Jurassic, Cretaceous and Palaeogene) occur to the southwest within parts of the Irish Sea Basin (Tappin *et al.*, 1994) but are absent within the northern part of the Cheshire Basin and beneath Ince Marshes. Their removal from the majority of the Cheshire Basin reflects widespread Cretaceous and Cenozoic exhumation (uplift and erosion) that also occurred across much of the UK (Holford *et al.*, 2005; Williams *et al.*, 2005). Apatite fission track analysis (AFTA) and vitrinite reflectance (VR) data demonstrate a polyphase exhumation history for the Irish Sea Basin with distinct exhumation phases occurring during the early Cretaceous (c.3 km), early Palaeogene (c.2 km) and late Palaeogene-Neogene (c.1 km) (Holford *et al.*, 2005). No AFTA or VR data are currently available from the immediate study area. However, VR data have been published from three wells located in Lancashire (Hesketh and Thistleton) and the adjacent offshore area (110/2b-10) (Figure 3.3). Measurements suggest that the SSG was buried rapidly following deposition to depths of c.1,950 m (110/2b-10) and c.3,800-4,200 m (Hesketh and Thistleton). Exhumation was initiated in southern Lancashire during the Mid Cretaceous, migrating progressively northwards through the Late Cretaceous to Early Palaeogene (Andrews, 2013). This implies that the onset of exhumation did not occur simultaneously across the EISB and it is possible that this is also the case with the neighbouring Cheshire Basin. Instead, it is likely that exhumation occurred sequentially as different structural elements became aligned to the contemporaneous tectonic stress regime.

The primary Late Mesozoic and Cenozoic driver of exhumation was northwards-directed Alpine crustal compression caused by collision of the Eurasian, Iberian and African tectonic plates (Ziegler *et al.*, 1995; Cloetingh *et al.*, 2005). During the Palaeogene, widespread exhumation resulted in the inversion of several Mesozoic basins across the UK, such as the Sole Pit-Cleveland basin, the Wessex and Weald basin and EISB with evidence for compressive stresses identified along the North Atlantic Margin (Stoker *et al.*, 2005). An additional temporary driver of exhumation during the Early Palaeogene was the migration (by continental drift) of western Britain and Ireland across the Iceland Mantle Plume (Jones *et al.*, 2002). In places where crustal thickening occurred (a process called magmatic underplating) the crust was effectively anchored and stabilised; however, adjacent un-anchored areas of crust became more buoyant and this resulted in rapid uplift and exhumation including areas bordering the Irish Sea Basin (Tiley *et al.*, 2004; Williams *et al.*, 2005; Westaway, 2009). Interpretations suggest that parts of the Irish Sea Basin have undergone up to 6 km of exhumation since the beginning of the Cretaceous, about 140 Ma (Holford *et al.*, 2005, 2009). Evidence for this exhumation is considered to also include the general absence of younger Mesozoic cover rocks – including by inference the Cheshire Basin, across large parts of northern Britain (Huuse and Clausen, 2001; Green *et al.*, 2012).



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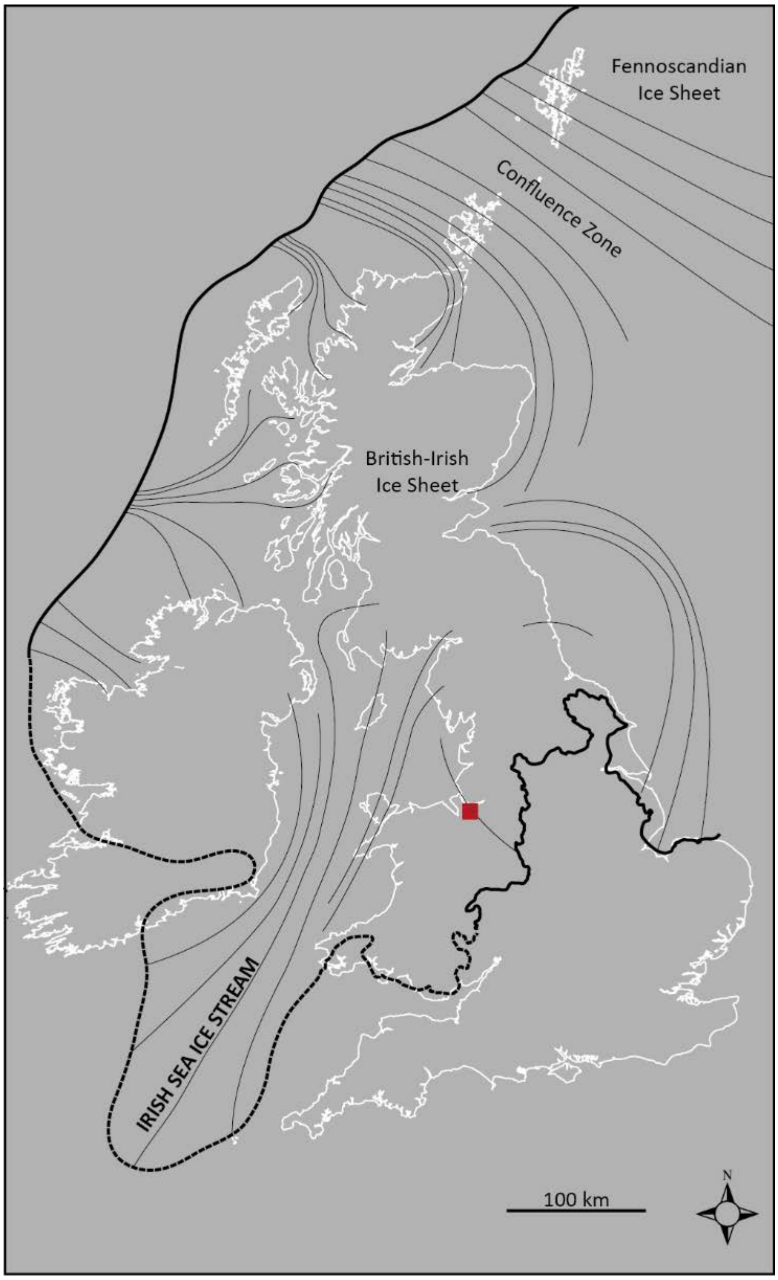
By the Late Miocene (c.11 Ma) the influence of the Alpine compression and the relative effect of magmatic underplating had either waned or ceased (in the case of the latter) as the UK migrated away from the Iceland Mantle Plume and the broader tectonic stress regime evolved (Figure 3.3). Instead, the primary driver of landscape evolution was climate-driven denudational isostasy (Westaway *et al*., 2002; Westaway, 2017). Denudational isostasy is a process driven by the relative uplift of the crust in response to the reduction of an applied load due to surface erosion (Bishop, 2007). In very general terms, the removal (erosion) of 1 km of crustal load is accompanied by approximately 0.85 km of crustal rebound (Bishop, 2007).



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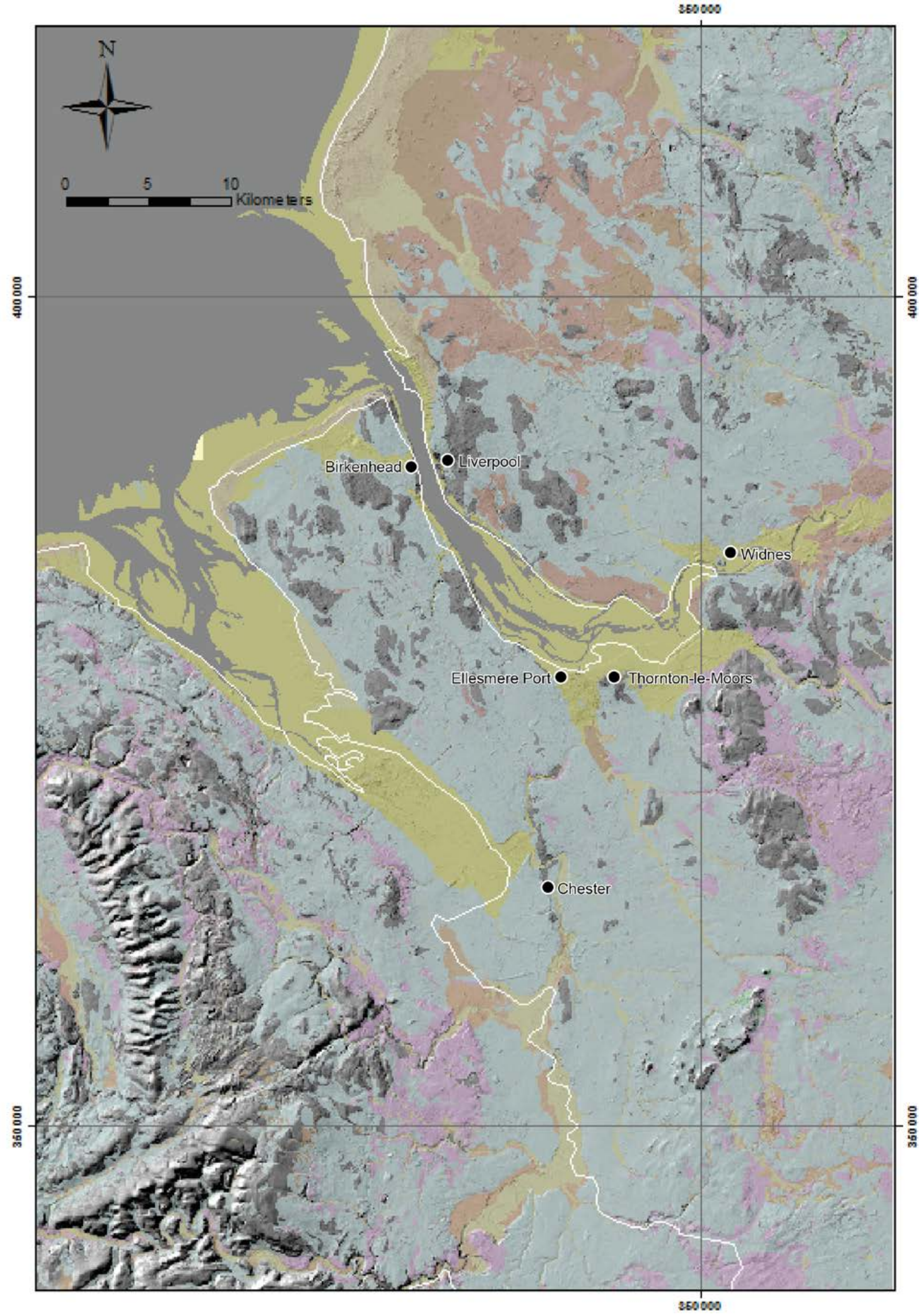

Figure 3.6. The superficial geology of the Cheshire Basin (CB) showing the distribution of major units (Digital geological map data BGS © NERC; contains Ordnance Survey data © Crown Copyright and database rights 2017.). Blue: Late Devensian till; Pink: Late Devensian glaciofluvial deposits; Orange: river terrace deposits; Yellow: Holocene coastal deposits. NEXTMap Britain elevation data from Intermap Technologies.

Throughout the Plio-Pleistocene, the global climate signal underwent a progressive intensification resulting in the strengthening of the glacial-interglacial climate signal. This drove changes in the distribution of solar insolation (heat) across the planet's surface, enhanced seasonality and the sequential establishment of regular cold-warm climate cycles over 21 ka (Pliocene), 41 ka (from c.2.6 Ma) and finally 100 ka (from c.1 Ma) time-scales. These climatic cycles, have amplified the dynamics of earth surface processes (e.g. weathering rates, vegetation cover and sediment availability) and the behaviour of geological systems (e.g. rivers, slopes, glaciers etc). Put simply, the landscape of the UK has become more dynamic over the past two and a half million years with progressively increased rates of weathering, erosion and sediment mobility (in response to denudational isostasy).

Throughout the Miocene-Pleistocene time-interval (23 Ma to 0.012 Ma), much of the EISB and most likely the Cheshire Basin were probably emergent. Major regional depositional centres include the Celtic Deep and St George's Channel troughs within the Irish Sea Basin, which accumulated between 100-200 metres of sediment (Tappin *et al*., 1994; Jackson *et al*., 1995; British Geological Survey, 2009). Subaerial exposure of the SSG and MMG means that the bedrock of the Cheshire Basin is likely to have been susceptible to modification by warm and cold-climate weathering and other landscape-forming processes. Cold climate periglacial and glacial processes are likely to have played a particularly significant role in modifying substrate properties during the past 2.6 million years. Weathering may have resulted in significant episodes of cement removal, fracture formation and natural hydraulic fracturing of the near-surface bedrock interval. Glaciers have been active agents in the British landscape periodically over the past 2.6 million years (Lee *et al*., 2011, 2012; Thierens *et al*., 2012). The largest glaciation occurred approximately 0.45 Ma (the Anglian) with ice sheets extending southwards towards London (Perrin *et al*., 1979; Bowen *et al*., 1986) and through St George's Channel and the Celtic Deep troughs (Tappin *et al*., 1994). Although no direct evidence occurs for this glaciation within the Cheshire Basin, the occurrence of erratic clasts from Cheshire (SSG) in tills in the West Midlands, demonstrates that ice crossed the study area from the Irish Sea Basin (Rice, 1968; Bridge and Hough, 2002). Much of the modern topography of the Cheshire Basin corresponds to the Late Devensian glaciation (c.27-17 ka) when the area was inundated by Irish Sea, Welsh and Lake District ice forming part of the Last British-Irish Ice Sheet (Price *et al*., 1963; Thomas and Chiverrell, 2007; Clark *et al*, 2012) (Figure 3.4). Glaciation (and deglaciation) of the Cheshire Basin resulted in the deposition of a variable thickness (locally exceeding 25 metres) of glacial deposits including tills, glaciofluvial and glaciolacustrine sediments which can be observed as the surface geology in much of the modern landscape (Figure 3.5; Price *et al*., 1963; Worsley, 1967; Johnson, 1968; Longworth, 1985; Wilson and Evans, 1990). Over much of the Cheshire Basin, these superficial deposits have largely (but not completely) buried the Triassic bedrock, with the latter likely to have been modified either by direct ice-bed traction and / or by glacial meltwater incision.

Following deglaciation, post-glacial sea-level rise and the re-establishment of regional and local drainage systems led to the formation of the largely subdued topography that now dominates the Cheshire Basin. This landscape is incised by rivers including the Mersey and Dee, and near the Mersey Estuary forms a low-lying coastal plain comprising Holocene-age coastal deposits.

3.3 SUMMARY

The Cheshire Basin and local study area possesses a long and complex geological history. A striking feature of its history being that rocks or sediments relating to the majority of its past 200 million years of evolution are absent having been removed by Late Mesozoic and Cenozoic exhumation. The following summary statements can be made about the post-Triassic history of the area:

- The Sherwood Sandstone Group is the youngest bedrock unit that occur beneath the Cheshire Energy Research Field Site.
- Following deposition during the Triassic these rocks were initially rapidly buried to depths of several kilometres (c.2-4 km). These remaining rocks may therefore exhibit properties (e.g. diagenetic, structural) that reflect processes that occurred in the crust to these depths.
- Since the Late Cretaceous, these rocks have been progressively exhumed with younger cover rocks having been removed by erosion. These rocks may therefore exhibit properties (e.g. structural) that reflect the progressive removal of a vertical load.
- The SSG and MMG within the study area are likely to have been sub-aerially exposed for several million years – possibly extending back into the Palaeogene. The primary properties of the near-surface intervals of the SSG and MMG are likely to have been modified by sub-aerial weathering (both cold and warm climate weathering) and other surface near-surface processes.
- During the last two and a half million years, the Cheshire Basin and study area have been glaciated on at least two separate occasions. Glaciation may have altered the SSG and MMG by direct ice-bed traction and/or by meltwater erosion.
- During the last (Late Devensian) glaciation, the SSG and MMG were largely buried by a veneer of superficial deposits including till, glaciolacustrine and glaciofluvial deposits.
- Following deglaciation, the Cheshire Basin and study area have formed an area of low-lying relief dissected by rivers and lying adjacent to the Mersey Estuary.

4 Conceptual Geological Model

4.1 DRIVER 1: PRIMARY AND SECONDARY BEDROCK PROPERTIES

A range of discontinuities occurs with the SSG, which reflect primary genesis and post-depositional secondary structures formed during burial and subsequent exhumation (Table 4.1). Discontinuities are a characteristic of the Sherwood Sandstone Group, and are seen in the Ince Marshes region at both outcrop and in borehole core. Bedding, including laminations and partings, are common within the SSG and reflect subtle variations in depositional flow regime and sediment supply. Fractures including faults (i.e. fractures with a measureable displacement) are common throughout the SSG and could form in relation to a variety of primary (e.g. syn-depositional dewatering) to secondary (e.g. soft-sediment deformation, dewatering, consolidation, lithification, unloading and seismicity) contexts. Fractures can be exploited by weathering and groundwater which can enhance the depth of weathering profile, groundwater mobility and chemistry. The occurrence of primary or secondary discontinuities such as fractures within the SSG is 'virtually certain'.

4.2 DRIVER 2: SUBAERIAL EXPOSURE AND WEATHERING

4.2.1 Cenozoic weathering

The bedrock geology beneath the study area is likely to have been subaerially exposed for several millions of years during the Cenozoic – possibly for much of the Neogene extending back in time to the Palaeogene. This restriction on 'accommodation space' limited where sediments could be deposited and critically their preservation. Palaeogene deposits occur discontinuously across southern East Anglia, the Thames Valley and southern England (Gale *et al*., 2006). Collectively, these support global records (Figure 3.3; Zachos *et al*., 2001, 2008) in demonstrating that so-called 'greenhouse climates' dominated and were generally much warmer and wetter than during later parts of the Cenozoic with several pronounced climatic optima (Westerhold et al., 2009) and cooling events (Hooker *et al*., 2004). Limited geological evidence exists for the Neogene within the UK. Heavily-degraded Miocene deposits crop-out within the Peak District and reveal a transition from sub-tropical, seasonally wet conifer-dominated forest to sub-tropical mixed forest (Pound and Riding, 2016). Pliocene-age deposits occur principally in southern East Anglia and whilst deposited against a backdrop of progressive global cooling are still considered to reflect climates that were probably warmer than the present day (Haywood *et al*., 2000; Johnson *et al*., 2000; Williams *et al*., 2009). Collectively, the prevailing tropical to temperate climatic conditions that prevailed during the Palaeogene and Neogene would have led to enhanced rates of chemical (e.g. saline water incursion, groundwater dissolution, soil development) and biological (e.g. root penetration, organisms) weathering (Huggett, 2011).

During the Quaternary, the prevailing climate changed significantly with a progressive intensification of the global climate signal and development of regular cold ('glacial stages') and warm ('interglacial stages') climatic cycles. Within the Early Pleistocene (c.2.58-1.2 Ma), major climate changes occurred with moderate frequency (approximately every 41,000 years) but their magnitude and influence on geological systems was relatively modest (Rose, 2010). Thus, whilst chemical and biological weathering was still active they were by no means the dominant geological agents. A globally-recognised interval, referred to as the Mid-Pleistocene Transition (1.2-0.6 Ma), records the amplification of glacial-interglacial cyclicity and switch to high-magnitude and low-frequency (approximately every 100,000 years) climatic oscillations. These acted to drive regular switches between extreme climatic regimes even in mid-latitude regions like Britain. During the optima of several interglacial events for example, palaeontological evidence demonstrate the presence of Mediterranean-style climates (i.e. high seasonal soil-moisture deficit) within Southern and Central Britain (Candy *et al*., 2010; Schreve and Candy, 2010). Geological evidence for temperate climate weathering includes the development of a range of soil types and chemical precipitates such as iron-pan and calcrete (Weil *et al*., 2016). By contrast, colder climates within Britain have supported the repeated development of permafrost (ground that occurs beneath the 0°c isotherm for over 2 years) and periglacial processes (Boardman, 2011; Busby *et al*., 2015). Simple conductive air-ground heat exchange modelling has demonstrated that permafrost thicknesses during the past 130 ka have within major cold stages exceeded over 100 metres depth (Busby *et al*., 2015). The combined effect of these warm- and cold-climate processes has, over the past one million years, led to dramatic increases in the mechanical (e.g. freeze-thaw, frost action), chemical (e.g. salt water incursion, groundwater dissolution, soil development) and biological weathering (e.g. root penetration, organisms) of materials exposed at or near to the surface (Rose, 2010).

Because of its lithological and textural properties, with poorly-cemented porous and permeable units, bedding discontinuities, fractures and faults, the SSG is highly-susceptible to **chemical** and **biological weathering** associated with glacial and post-glacial processes and weathering (Yates, 1992). Indeed, a study by Mottershead *et al*. (2003) highlights the role of chemical and biological weathering and specifically the influence of marine salt crystallisation on weathering rates. Their study concluded, for example, that the presence of marine salts resulted in the acceleration of weathering rates by a factor of 1.59 (Mottershead *et al*., 2003). Thus, saline water incursion into the SSG during successive global marine high-stands throughout the Cenozoic would have likely-resulted in enhanced salt weathering rates (Trenhaile and Mercan, 1984; Williams and Robinson, 2001). Weathering under longer-term cold climates is likely to include carbonate dissolution (greater at lower temperatures), salt weathering and frost weathering (mechanical weathering).

Frost weathering is another significant weathering process that may affect the SSG (Walder and Hallet, 1986; Matsuoka, 1990; Matsuoka and Murton, 2008). Ice formed by the freezing of water within the void (pore) space between rock and sediment particles is called *pore ice*. The pressure exerted by the expansion in volume that occurs during the conversion of water to ice can cause a rock to mechanically fail. The growth of pore ice and susceptibility of a rock or sediment to failure will depend on: (1) the maintenance of an elevated water-table; (2) the void (pore) space within a rock or sediment and ease with which water can enter the pore space (related to permeability); (3) a greater ice volume to pore-space ratio. Due to its porosity, the SSG would be highly-susceptible to the growth of pore ice. Mechanical weathering of a rock or sediment can also occur by the growth of ice (called *segregated ice*) within isolated layers or lenses. The formation of ice by this mechanism requires strong capillary forces (the molecular force that exists between confined rock or sediment particles) to be active and these are typically greater in finer-grained rocks and sediments with lower void space. Increased capillarity enable elevated levels of cryosuction to build-up (Taber, 1929) which acts to pull additional water into the zone of freezing forming segregated ice that grows in the direction with which heat is being most rapidly conducted away (i.e. towards the ground surface) (Williams and Smith, 1989). Finer-grained horizons within the SSG are likely to be frost-susceptible with the growth of *segregated ice* causing mechanical breakdown of the parent material.

The wide range of weathering mechanisms that operated during the Cenozoic, combined with the properties of the SSG, make it susceptible to specific forms of weathering (Table 4.1). Strata that have been exposed at or near to the land-surface for prolonged periods of geological time, and/ or strata that have been inundated by saline groundwater are particularly susceptible to weathering. Rock strata that have undergone varying degrees of *in situ* weathering in their ultimate conversion to soil are referred to as saprolites.

FEATURE	DESCRIPTION	GEOMETRY	IMPACT	LIKELIHOOD OF OCCURRENCE
	DRIVER 1: Primary and Secondary Bedrock Properties			
Bedrock discontinuities	Primary laminations and partings; fractures; fault zones.	Primary laminations and partings parallel to sub-parallel to bedding; fractures and faults may be of variable geometry.	Discontinuities may provide enhanced pathways into the bedrock volume for weathering processes.	Virtually certain
	DRIVER 2: Subaerial exposure and weathering			
Long-term weathering	Weathered or partly-weathered bedrock strata. Strata may be de-structured and de-cemented. Potential occurrence of buried palaeosol horizons including iron-pan and calcrete.	Discontinuous and variable saprolite thickness. Generally likely to be up to 10 metres thick but locally may be thicker.	Unconsolidated or poorly-consolidated bedrock; can lead to complex geotechnical and hydrogeological properties and difficulties in the discrimination of bedrock and superficial deposits.	Virtually Certain
	DRIVER 3: Glaciation			
Buried Valleys	Buried channels incised into substrate that have little or no surface expression in the modern landscape. Saprolite is commonly absent in buried valleys.	Variable scale. Typically tens of metres deep and hundreds of metres wide (sometimes >km).	Enhanced hydraulic conductivity between the surface and shallow sub-subsurface, depending on properties of fill.	About as likely as not
Till sheets	A laterally-extensive sheet of glacial till.	Variable thickness but commonly several metres thick. May be discontinuous if subsequently eroded.	Can provide relative barriers to groundwater mobility; alternatively, may be sand-prone and fractured and allow communication between surface and subsurface.	Very likely
Lenses within till sheets	Discrete lenses of sand and gravel, sand or silt and clay.	Discontinuous, variable thickness	Enhanced or reduced hydraulic conductivity between the surface and shallow sub-subsurface.	About as likely as not
Till fractures	Small-scale often 'closed' fractures (e.g. faults or joints).	Sub-horizontal and / or sub-vertical geometry; variable lateral and vertical continuity.	Enhanced hydraulic conductivity between the surface and shallow sub-subsurface.	Virtually Certain (if till present)
Basal decollement surface	Sharp structural detachment at the base of a till sheet.	Undulating but generally sub-horizontal geometry.	Large-scale sub-horizontal shear planes can be prone to failure.	About as likely as not
Large-scale folding and thrusting	Large-scale fold and thrust complexes that result in the structural re-ordering of the pre-existing stratigraphy.	Variable geometry depending on boundary conditions during formation. Deformation likely to occur over thicknesses of up to several tens of metres.	Large-scale shear planes that can be prone to failure; increased hydraulic conductivity.	About as likely as not
Glacitectonic rafts	Rafts of translocated substrate (e.g. bedrock) transported down-ice and deposited out-of-sequence.	Variable scale but may be over 10 metres thick.	Large-scale shear planes that can be prone to failure; increased hydraulic conductivity.	About as likely as not
Meltwater Hydrofractures	Meso-scale fracture systems that can deform bedrock and superficial strata. Fractures can be 'closed' or infilled (i.e. 'open') by stratified sediment.	Sub-horizontal to sub-vertical in geometry often several metres length.	Enhanced hydraulic conductivity between the surface and shallow sub-subsurface.	About as likely as not

Heterogeneous sediments	Stratified sorted meltwater sediments including clays, silts, sands and gravels.	Often highly-variable with complex geometric relationship and variable contacts (e.g. sharp, intercalated or gradational).	Enhanced hydraulic conductivity between the surface and shallow sub-subsurface.	Very likely
Groundwater flushing beneath permafrost	Increased hydraulic head builds up the proglacial permafrost, with the potential to drive meltwater hundreds of metres into bedrock, flushing porewaters.	May influence bedrock porewaters up to hundreds of metres laterally and vertically from the glacier snout	Porewater flushing with meltwater	About as likely as not
DRIVER 4: Post-glacial				
Post-glacial isostatic rebound	Increased seismicity, fault reactivation and fracturing		Enhanced hydraulic conductivity between the surface and shallow sub-subsurface.	About as likely as not
Sea-level change	Saline groundwater incursion		Aquifer contamination; hydraulic conductivity between shallow sub-surface and sea bed.	Very likely
Aeolian sequences	Coversands with thin peat layers which can give rise to compressible ground	Thin, metre-scale.	Generally free-draining with local low permeability (peat) strata; peat may be liable to compression when loaded.	About as likely as not

Table 4.1. Features that may be present beneath the Cheshire Energy Research Field Site and give rise to unpredictable sub-surface behaviour.

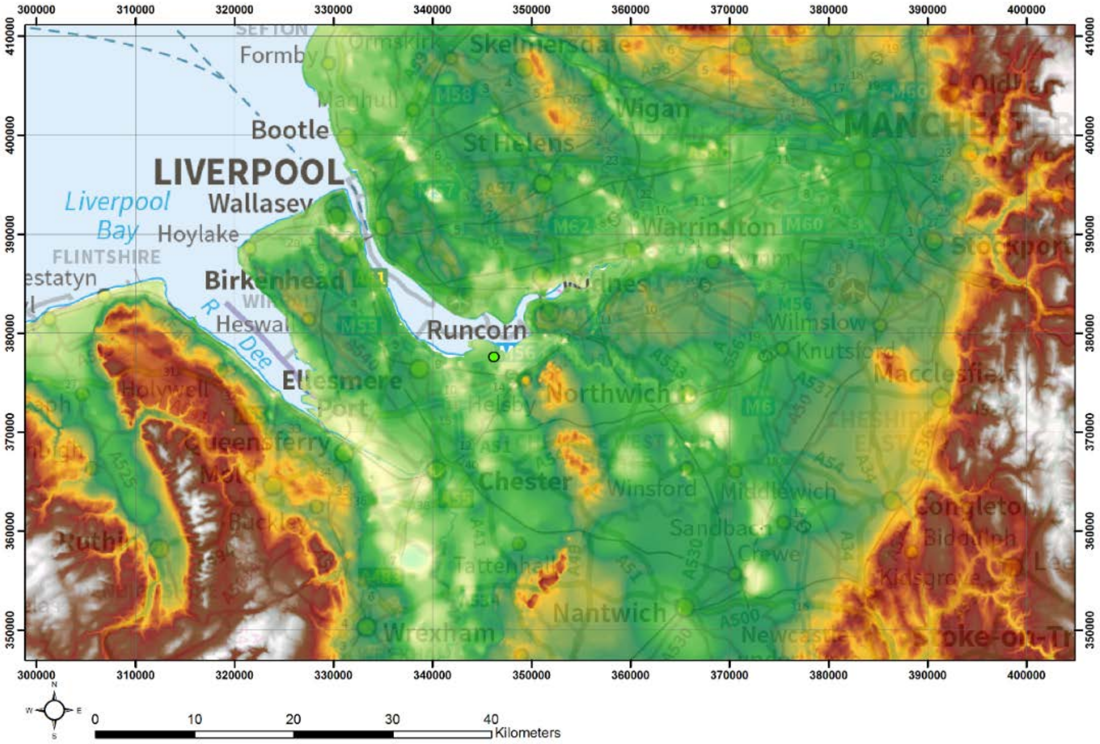

Figure 4.1. A rockhead (geological) relief model for the northern Cheshire Basin including the study area (green dot). Pale yellow and pale green areas of shading correspond to areas of lowest rockhead relief and, where connected, the location of major buried valleys. Includes Ordnance Survey data © Crown copyright and database rights [2017] Ordnance Survey [100021290 EUL].

Saprolites developed on the SSG may comprise partly or completely de-structured sandstone (sand) or gravel where the cement that bonds individual sand particles has weakened or been removed. Restricted areas of 'weathered bedrock' derived from the Sherwood Sandstone Group, up to a maximum of 20 m thick, have been identified by Burke *et al*., (2016) within the Cheshire Energy Research Field Site. Localised re-sedimentation of the saprolite may also have occurred in response to more recent fluvial activity or downslope movement. The thickness and extent of this material in the study area is difficult to determine due to the paucity of data. However, in a recent study based on the SSG in the East Midlands, Tye *et al*. (2011) found that the depth of weathering reached a maximum of 40 metres. Weathering rates were greatest where faulting allowed meteoric waters to penetrate downwards to greater depths within the bedrock. Therefore, saprolite of discontinuous distribution and variable thickness (perhaps up to 40 metres) is 'virtually certain' beneath much of the study area.

4.3 DRIVER 3: GLACIATION

The Cheshire Basin has been glaciated on at least two occasions during the Quaternary. The last glaciation, corresponding to the Late Devensian, resulted in the region being overridden by ice from two sources. Firstly, Welsh ice originating from Snowdonia and the Arenig Mountains of north Wales (Thomas, 1985; Jansson and Glasser, 2005). Secondly, Irish Sea / Lake District ice that extended southwards through the Irish Sea Basin with an eastern offshoot directed across Lancashire into Cheshire, Staffordshire and the West Midlands (Boulton and Worsley, 1965; Thomas, 1985; Thomas, 1989; Parkes *et al*., 2009; Chiverrell *et al*., 2016). Welsh ice was restricted to the western side of the modern River Dee with the study area overridden by Irish Sea ice (Howard *et al*., 2007).

4.3.1 Buried Valleys (Meltwater erosion)

A striking feature within the northern part of the Cheshire Basin is the highly irregular rockhead surface with several deeply-incised buried valleys ranging up to tens of metres deep recognisable (Figure 4.1). Several buried valleys have been identified beneath modern rivers including the Dee and Mersey (Reade, 1873, 1885; Boswell, 1925, 1937; Jones, 1937; Gresswell, 1964; Howell, 1973; Crofts, 1999; Burke *et al*., 2016) and elsewhere in Cheshire (Owen, 1947; Worsley *et al*., 1983).

The consensus within the literature is that these buried valleys were produced by glacial over-deepening (subglacial erosion) and / or subglacial meltwater incision (Gresswell, 1964; Howell, 1973). Buried valleys produced by subglacial meltwater incision are commonly called tunnel valleys (or tunnel channels in North America) and occur widely around former glacier margins (Ó Cofaigh, 1996; Piotrowski, 1997; Kristensen *et al*., 2008; Dürst Stucki *et al*., 2010; Kehew *et al*., 2012). Incision of tunnel valleys occurs under immense hydraulic gradients with flow regimes constrained by channel morphology and the thickness of overlying ice. A common characteristic of tunnel valleys is that their bases (referred to as the thalweg) are often undulating with significant normal and reverse changes in gradient developed along their long-profile. Infills to buried valleys tend to be highly-chaotic encompassing intercalated beds of till, glaciolacustrine (silt and clay) and glaciofluvial (sand and gravel) sediment that typically give-rise to chaotic and unpredictable hydrogeological behaviour.

The rockhead surface model provides a valuable insight into the nature of the rockhead surface beneath the study area. However, it only provides a generalisation of the rockhead surface with local variation also influenced by relative borehole density. The model shows a radial arrangement of buried valleys fanning outwards from the Liverpool-Skelmersdale area southwards and eastwards beneath the Cheshire / north Shropshire lowlands (Figure 4.1). The radial pattern conforms to the geometry of the hydraulic gradient that would generate perpendicular to the margins of a piedmont-style glacier lobe that fanned outwards across the Cheshire lowlands towards the west, south and east. This style of glacier geometry has previously been inferred for the Late Devensian ice lobe based upon the mapped distribution morainic landforms around the region (Boulton and Worsley, 1965; Yates, 1967; Thomas, 1989).

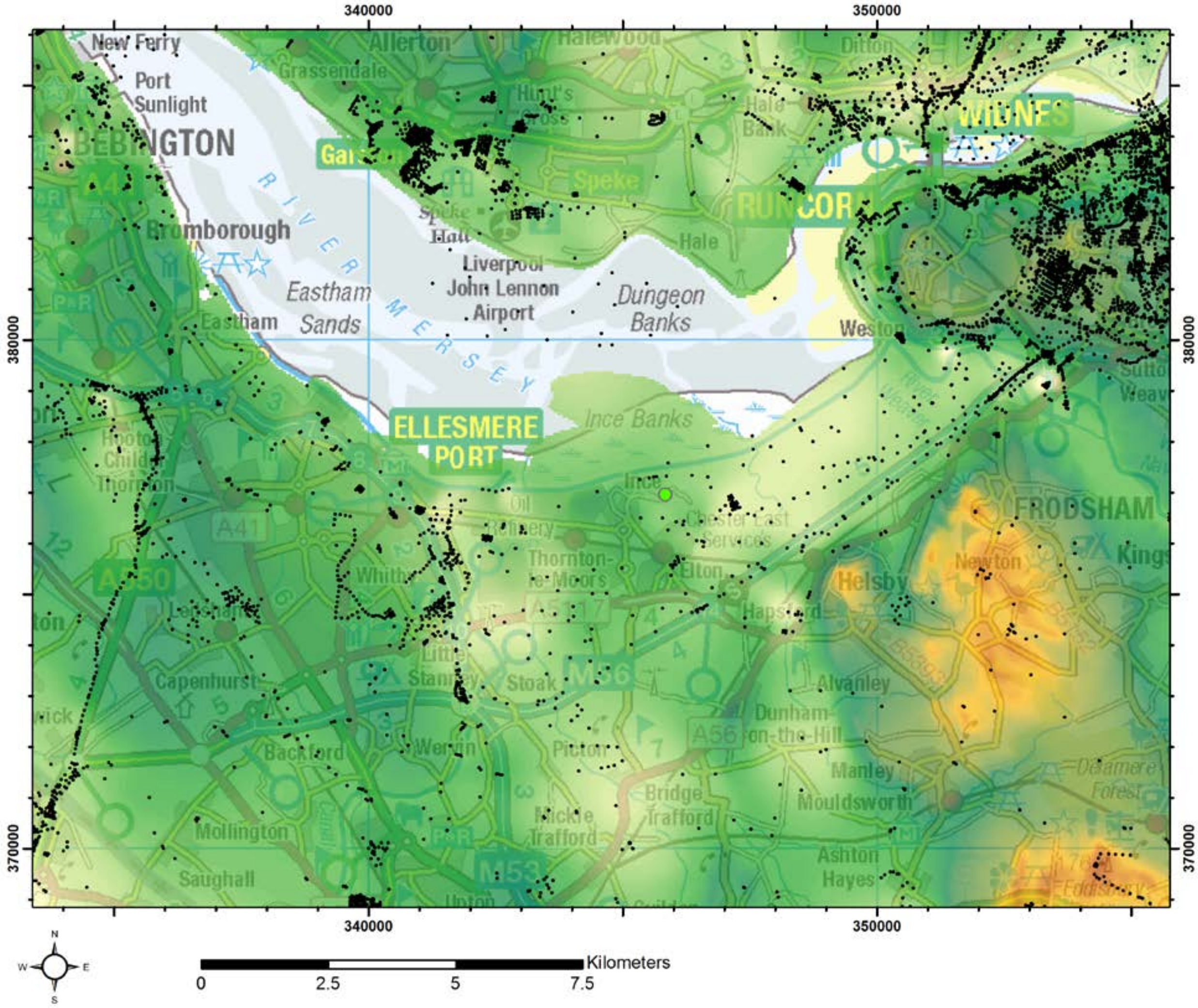

Figure 4.2. Rockhead (geological) surface model adjacent to the Cheshire Energy Research Field Site (green dot) showing a major buried valley (pale yellow to pale green) to the west extending northwards to Ellesmere Port joining an assumed valley that extends beneath the Mersey Estuary. Borehole locations are indicated by small black dots. Includes Ordnance Survey data © Crown copyright and database rights [2017] Ordnance Survey [100021290 EUL].

Whilst a glacial origin for several of the larger buried channels is logical, some channels may have existed in the landscape prior to the Late Devensian glaciation and originally be of fluvial origin. For example, Worsley *et al*. (1983) describes a buried channel that contains preglacial organic sediments overlain by glacial till and meltwater sediments. Of particular relevance to the study area is the existence of a major buried channel beneath the modern River Mersey (Figure 4.2). Small, broadly north-south trending offshoots of this buried valley occur to the west and east of Thornton-le-Moors. However, the resolution of the rockhead model mean that the true geometry of these buried valleys remains poorly constrained. Therefore, the presence of a buried valley beneath the Cheshire Energy Research Field Site is 'about as likely as not' (Table 2.1). Local perturbations in the rockhead surface up to 47 m below OD, some likely associated with buried channels, have been identified to the east of the village of Elton, beneath Ince Marshes and are described by Burke *et al*. (2016).

Figure 4.3. A coastal section through Irish Sea-derived till from Anglesey, north Wales.

4.3.2 Tills (internal fractures)

Two lithologically-similar sheets of Irish Sea-derived till have been recognised adjacent to the Mersey (Thomas, 1989) (Figure 4.3). They comprise over-consolidated, variably stony (matrix- to clast-supported), red-brown diamicton containing a mixture of locally-derived SSG and MMG material, and far-travelled clast lithologies derived from the Lake District and southwest Scotland (Wedd *et al*., 1923). Exposures of the Irish Sea Till in Cheshire are limited but several sections have been described and reported at Thurstaston on the Wirral Peninsula (Slater, 1929; Brenchley, 1968; Glasser *et al*., 2001). Till sheets directly overlie one another or bedrock, or are locally underlain and separated by a variably-thick sequence of glacilacustrine silts and clays and glacifluvial sands and gravels (Brenchley, 1968; Worsley *et al*., 1983; Earp and Taylor, 1986; Crofts, 1999). Either or both till sheets are 'very likely' to be present beneath the study site and may locally attain thicknesses in excess of 20 metres (Crofts, 1999).

Although there are no known exposures of till in the study area, most subglacial tills contain horizontal and vertical fractures produced by compressional stresses (e.g. reverse or thrust faults), or extensional stresses including unloading (e.g. joints, normal faults) (Figure 4.4; Williams and Farvolden, 1967; Derbyshire and Jones, 1980; Eyles and Sladen, 1981; Evans *et al*., 2006). Their presence – assuming a till sheet(s) is present beneath the site is 'virtually certain' (Table

4.1). Equally, tills often contain discrete lenses (discontinuous) of sand, sand and gravel, or clay and silt and their occurrence within till – if present beneath the search site, is 'about as likely as not' (Table 4.1).

Figure 4.4. An example of a heavily-fractured till, east Yorkshire, showing vertical and horizontal joint sets.

4.3.3 Glacitectonic Structures (folds and thrusts)

The process of glaciation is widely treated as a sedimentary process. However, the action of glaciers overriding and interacting with a pre-existing landscape is actually a tectonic process and akin in many respects (but not all) to continental-scale processes that occur with mountain belts and shear zones (Pedersen, 2012; Lee *et al*., 2017). The action of glaciers overriding and pushing into a pre-existing landscape can cause the widespread deformation of existing materials. Deformation can take place in a spatial continuum from subglacial (beneath the ice), ice-marginal (beneath or adjacent to the ice margin) or proglacial (in front of the glacier) (Benn and Evans, 2010).

The base of major till sheets are commonly marked by a structural zone exhibiting glacitectonised substrate materials and bounded by variably-extensive sub-horizontal decollement surfaces (Banham, 1977; Berthelsen, 1978; Boulton and Hindmarsh, 1987; Hart, 1995; Evans *et al*., 2006; Aber and Ber, 2007; Lee and Phillips, 2013). The thickness of these shear zones (encompassing glacitectonised substrate and till) can vary from metre-scale to tens-of-metre scale depending on substrate rheology (controlled by substrate lithology, porewater availability and temperature), and the degree of ice-bed traction (Boulton and Hindmarsh, 1987; Boulton, 1996; Murray, 1997; Evans *et al*., 2006; Kjær *et al*., 2006; Lee and Phillips, 2013; Phillips *et al*., 2013). Their presence beneath the study site is 'likely' (Table 4.1). However, distinguishing between till and glacitectonised bedrock may prove problematic. This is because the appearance of both the till and glacitectonised bedrock may be similar and detailed laboratory analyses (e.g. strength, lithology, palynology) may be required to delineate them.

Terminal moraines are produced by the 'bulldozing' and pushing of ice-marginal and proglacial materials at the snout of a glacier and their geometry often mirrors the form and dynamics of the glacier margin (Boulton, 1986; Krüger, 1993; Aber *et al.*, 1995; Harris *et al.*, 1997; Bennett, 2001). The construction of terminal moraines leads to the development of fold and thrust complexes similar (albeit much smaller) to those that form in continental-scale foreland fold-thrust zones within orogenic belts (Croot, 1987; Aber and Ber, 2007). The formation of a variety of fold and fault styles can alter the geometry and relative ordering of the main stratigraphic units bringing different units into juxtaposition (Figure 4.5; Slater, 1931; van der Wateren, 1985; Hart, 1990; Aber, 1993; Harris *et al.*, 1997; Phillips *et al.*, 2007; Roberts *et al.*, 2007; Phillips *et al.*, 2008; Thomas and Chiverrell, 2011; Lee *et al.*, 2013). The likely occurrence of these features beneath the study site is 'about as likely as not' (Table 4.1). Commonly associated with this style of glacitectonism are the development of glacitectonic rafts. These are dislocated slabs or bedrock or cohesive sediment that have been detached along rheological discontinuities, transported by thrusting and deposited out-of-sequence down-ice (Ruszczynska-Szenajch, 1987; Aber and Ber, 2007; Burke *et al.*, 2009; Vaughan-Hirsch *et al.*, 2013). The geometry of glacitectonic rafts can vary markedly from metre-scale to tens and even hundreds of metres.

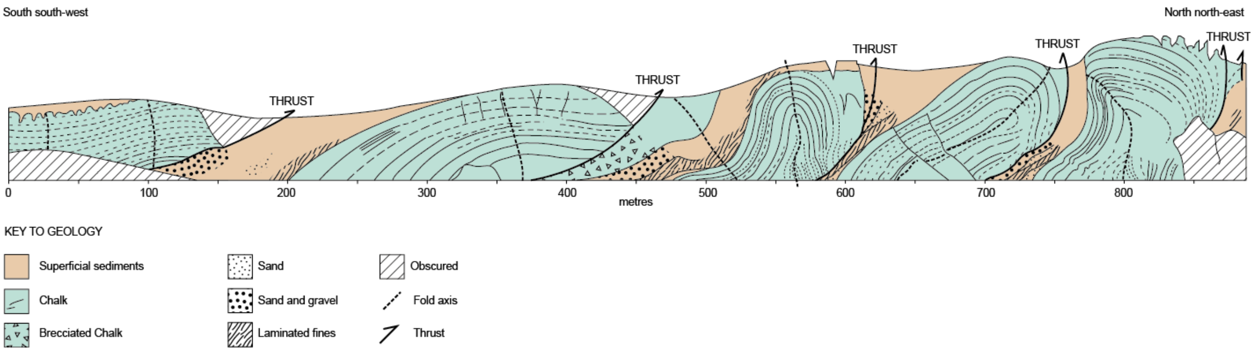

Figure 4.5. Structural interpretation of deformed bedrock and superficial sequences at Møens Klint, Denmark (from Lee and Phillips, 2013).

Within the Cheshire Basin (CB), a tripartite glacigenic sequence comprising two tills and intervening outwash deposits has been described (Worsley, 1991; Crofts *et al.*, 2005). They were laid-down in association with a lobe of wet-based Irish Sea Ice that extended across the Cheshire / Shropshire lowlands reaching as far south and west as the West Midlands. Evidence from both modern glacial environments and the geological record suggests that key controls on ice-bed interactions and in-turn glacier behaviour is meltwater availability (Eyles, 2006; Bell, 2008). Within the CB, given the lateral continuity of the major till facies, it suggests that ice-bed traction was largely limited with a meltwater-enhanced substrate zone effectively decoupling the glacier from its bed. This would have limited the transmission of strain into the substrate. Reducing and / or varying the availability of meltwater within the substrate typically has the effect of enhancing ice-bed traction enabling the transmission of strain into the glacier bed (Lee *et al.*, 2017). This dramatically increases the potential for larger-scale deformation of the substrate including the development of glacitectonic folds, faults and bedrock rafts. Therefore, during collapse of the Irish Sea Ice and progressive northwards retreat of the ice margin across the CB, temporal and spatial variations in substrate water availability may have led to enhanced ice-bed traction and in-turn substrate deformation by glacitectonic processes. This effect of often amplified where the substrate is dominated by permeable lithologies (e.g. SSG) which act as meltwater sinks and

/ or where seasonal freezing of the glacier snout to its bed occurs (e.g. Hiemstra *et al*., 2007; Lee *et al*., 2013, 2017).

Evidence for these glacitectonic processes occurring in the CB is indicated by the development of terminal moraine complexes (Boulton and Worsley, 1965; Thomas, 1989; Price *et al*., 2007; Parkes *et al*., 2009; Clark *et al*., 2012; Crofts *et al*., 2012). To date, no glacitectonic rafts have been identified within the Cheshire Basin. However, the style of deglaciation coupled with the prevailing climatic conditions and hydrogeological properties of the SSG make it particularly susceptible to the development of these structures. The likely occurrence of these features beneath the study site is 'about as likely as not' (Table 4.1).

4.3.4 Hydrofracture Systems

Another important feature recognised within glacial sequences and associated bedrock units are meltwater hydrofracture systems. These can develop within a range of different glacial systems where substrate water availability is high or seasonally variable (van der Meer *et al*., 1999; Phillips, 2006; Roberts *et al*., 2009; Phillips *et al*., 2013; Lee *et al*., 2015). Hydrofractures are generated by the catastrophic failure of material in response to the release of over-pressurised porewater. Hydrofractures can exhibit a range of different geometries that are unique to the boundary conditions at the time of fracturing. Typically, a single hydrofracture is millimetre to tens of centimetres wide, and metres to tens of metres in length; complex hydrofracture networks can develop within the bedrock succession (e.g., Cowsill *et al*., 2016). If a hydrofracture has been reactivated then it can contain a stratified sediment fill when can prevent the fracture from re-sealing enabling further hydrofracturing and draining of the substrate (Phillips, 2006). Hydrofractures have been widely reported from the Sherwood Sandstone Group (Hough *et al*., 2006) and more locally at Runcorn (Weathall *et al*., 2001) and near Preston (Cowsill *et al*., 2016). The elevated and variable meltwater availability that controlled the dynamics of the Irish Sea Ice lobe offer suitable conditions for their development. The likely occurrence of these features beneath the study site is 'very likely' (Table 4.1).

4.4 DRIVER 4: POST-GLACIAL

4.4.1 Post-Glacial Isostatic rebound

Since the last glaciation, rates of isostatic adjustment due to unloading of glacier ice from the crust in the UK are well documented (Shennan *et al*., 2006). Isostatic adjustment can lead to an increase in seismicity, fault reactivation and crustal fracturing where strain stored within the crust is released as the vertical load is removed (Firth and Stewart, 2000; Stewart *et al*., 2000). The Cheshire Basin lies within an area of positive isostatic adjustment (uplift) and is therefore prone to rebound-related seismicity and fracturing (Shennan and Horton, 2002). The likely occurrence of fractures relating to isostatic rebound are 'about as likely as not'.

4.4.2 Sea-level change

Following the retreat and melting of the glaciers at the end of the Late Devensian glaciation global sea-levels rose drowning previously exposed (and glaciated) areas of continental shelf and basinal areas including the Irish Sea. Immediately following deglaciation, a new drainage system became established including the River Mersey with a major period of sedimentation and stabilisation during the early Holocene (c.9,600-8,000 yrs BP) (Tooley, 1974; Macklin *et al*., 2010;

Roberts *et al.*, 2011). Continued sea-level rise during the Holocene is likely to have resulted in the transition from terrestrial (fluvial?) to estuarine (proximal) and finally estuarine (distal) as continued sedimentation led to emergence of the coastal plain. Regional sea-level rise around the Mersey Estuary is 'very likely' to have led to saline groundwater incursion into the SSG depending on the hydraulic connectivity between the bedrock, overlying superficial deposits and seabed.

Additional geological features that may occur beneath the Cheshire Energy Research Field Site are aeolian sediments and inter-stratified peat horizons. Aeolian activity adjacent to the Irish Sea Basin was widespread following the end of the last glaciation because of the high-availability of suitable sediment (pre-existing glacifluvial deposits) and the prevailing climatic conditions (Wilson *et al.*, 1981). Extensive sand dune systems are present in coastal areas of Cheshire and Lancashire (Gresswell, 1937; Pye and Neal, 1994), North Wales and Anglesey (Greenly, 1919; Ranwell, 1959; Bailey and Bristow, 2004) and an aeolian coversand (the Shirley Hill Sand Formation) has also been recognised in parts of the region (Wilson *et al.*, 1981; Howard *et al.*, 2007). Commonly associated with coversand and dune systems are thin discontinuous horizons or beds of peat. These typically form as thin immature soils or peat development within localised poorly-drained inter-dune areas. The presence of aeolian deposits of variable thickness beneath the study area, including sand (coversand) or loess (silt), is 'about as likely as not'. Accumulations of peat have also been identified offshore of the Wirral (Innes *et al.*, 1990; Kenna, 1986) and some of these may be contemporaneous with peat units identified by Burke *et al*. (2016) within coastal deposits. Peats can acts as local aquitards and give rise to compressible ground conditions when loaded. Their presence within coastal deposits is 'very likely'.

4.5 CONCEPTUAL GEOLOGICAL MODEL OF THE STUDY AREA

Based upon the narrative outlined above it is possible to predict the natural superficial geology beneath the Cheshire Energy Research Field Site area and this is shown below in a schematic cross-section (Figure 4.6). Many of the features identified in this conceptual model have been described at the Cheshire Energy Research Field Site by Burke *et al*. (2016).

In summary, based upon the application of the conceptual geological model methodology, the following features may need to be considered in any sub-surface ground investigations.

- Unweathered bedrock (Sherwood Sandstone Group) will be largely buried by natural superficial deposits beneath much of the search area. Bedrock is predicted to be mantled by a weathered zone of variable thickness and extent. Bedrock and weathered bedrock may be deformed by hydrofractures and by glacitectonic thrusting.
- The rockhead surface is predicted to be irregular reflecting both weathering of the bedrock and the possible presence of buried channels produced by meltwater incision.
- A glacial succession of variable thickness is predicted to be present beneath the much of the search site. It drapes the bedrock (or weathered bedrock) infilling buried channels that may be present and comprising a highly-variable succession of till, laminated silt and clay, sand and sand and gravel.
- The glacial sequence is predicted to be heterogeneous composed largely of till with localised discontinuous bodies of sand and laminated silt and clay. Till units are predicted to be deformed by vertical and horizontal joints, large-scale thrusts and / or folding and possibly by hydrofractures.

Holocene-age coastal deposits are predicted to overlie and, in places (e.g. tidal channels), truncate the glacial succession. These deposits are predicted to be heterogeneous and highly-complex comprising beds of peat, sand, silt and clay and gravel.

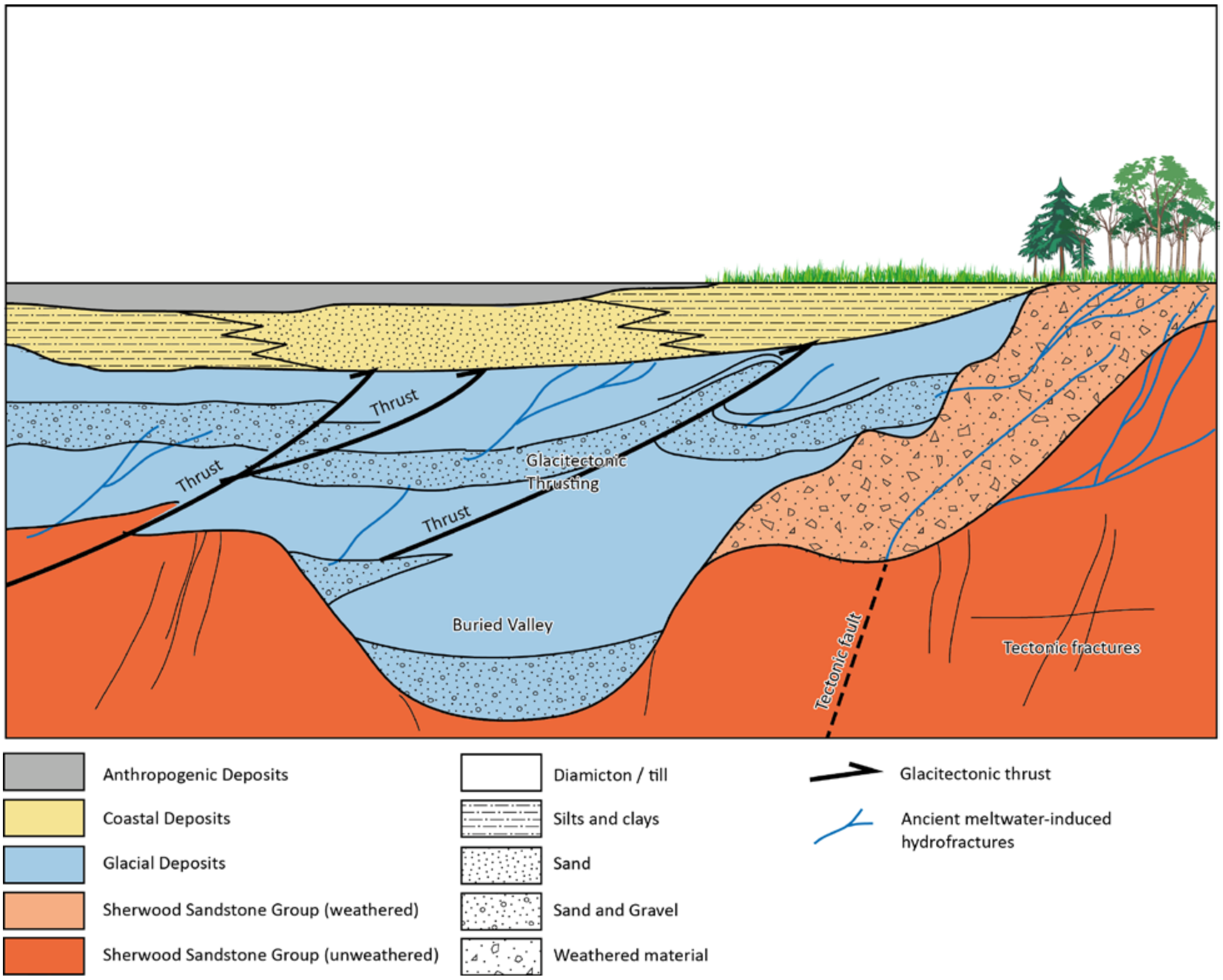

Figure 4.6. A schematic model (not to scale) showing the predicted natural superficial geology beneath the search area. The ground surface slopes from south to north.

5 Conclusions

- This study of the superficial geology of the Ince Marshes area employs a conceptual approach to predicting the range of geological features that may be recorded in the geology. The approach is underpinned by the known range of large-scale geological processes and environments that have affected the area. The approach also employs a measure of uncertainty to quantify the likely occurrence of a geological feature.
- Weathering of buried bedrock strata (Sherwood Sandstone Group) should be considered 'virtually certain' beneath the study area although its distribution and thickness could be variable. Any zone of weathering is likely to contain strata in various states of conversion to soil. The occurrence of weathered bedrock strata within buried valleys is likely to be more limited due to erosion by fluvial and meltwater processes.
- The sub-drift (rockhead) surface regionally is highly-irregular and this is also likely to be apparent beneath the search area. Rockhead could be influenced by depth of weathering as well as buried valleys produced by meltwater and glacial erosion which are 'about as likely as not' to be present.
- Bedrock strata are likely to be buried beneath a sequence of glacial (till and sorted sediments) and non-glacial (fluvial and estuarine) deposits. On a regional scale, glacial sediments are likely to form a broad layer-cake succession comprising a till sheet(s) and associated meltwater deposits. At the local scale, deformation structures including faults, folds, joints and hydrofractures may also be present and penetrate down into and deform the bedrock.
- Non-glacial deposits probably form the cap to the sequence beneath the study site and were deposited following deglaciation. These are also likely to be heterogeneous.
- Fully understanding the complexity of the natural superficial sequence beneath the study area and its relationship to the modern ground surface and bedrock will require the integration of numerous datasets (borehole, shallow geophysics, site investigation), interpreted within the regional understanding of the conceptual geological model and processes that have been active at the Cheshire Energy Research Field Site.

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