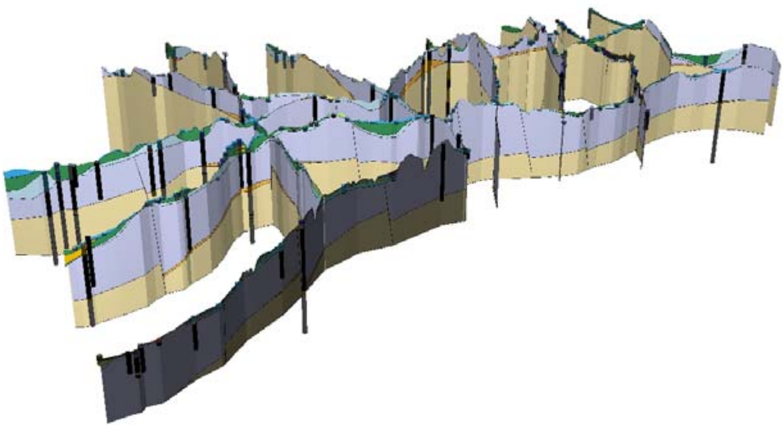
Superficial Geology and Hydrogeological Domains between Durham and Darlington Phase 2 (Durham North)

Report prepared for the Environment Agency by the British Geological Survey

Commercial Report CR/07/022N



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Superficial Geology and Hydrogeological Domains between Durham and Darlington Phase 2 (Durham North)

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Geological fence diagram for Durham North area.

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Foreword

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1 Introduction

The North East Region's Groundwater Modelling Strategy has identified the need for the development of a conceptual model for the Magnesian Limestone aquifer. In line with the Environment Agency R&D Technical Report W214 (Environment Agency Framework for Groundwater Resources Conceptual and Numerical Modelling), a scoping study was produced, that identified areas of uncertainty and work required for the development of the conceptual model.

The purpose of this project is to give the Environment Agency (EA) a regional understanding of the geology and hydrogeology of the Magnesian Limestone and overlying superficial deposits in the North East Region, using information held by the British Geological Survey (BGS). This report contributes to the conceptual model and understanding of the Magnesian Limestone aquifer.

There is uncertainty in the amount of recharge that the Magnesian Limestone receives from rainfall. The project is designed to gain a greater understanding of the geology of the superficial deposits and their hydrogeological properties. These are the key factors for the calculation of recharge to the Magnesian Limestone aquifer from rainfall. This element of the conceptual model is essential in understanding the potential water resource available within this aquifer.

1.1 SCOPE

The scope of the BGS project is to provide an interpretation of the geology of the superficial deposits overlying the Permian strata of the Durham area and to derive hydrogeological domains within them. It is important to note that the hydrogeological domains were derived from a computer analysis of interpreted boreholes within the project area. This was a separate exercise from the production of the geological cross-sections.

The geological sequence of interest comprises the Carboniferous Coal Measures, Namurian Stainmore Formation and the basal Permian Yellow Sands, which lie beneath the Permian Magnesian Limestone and Marls. This phase of the study set out to interpret the regional geology of the superficial deposits lying above the bedrock sequence and develop hydrogeological domains within them, similar to those produce for the Manchester urban study (Crofts *et al.*, 2006). These hydrogeological domains will be used by the EA to develop a recharge model for the Magnesian Limestone aquifer and will be integrated into current projects.

This study area has been split into the following 3 phases for management purposes and to meet deadlines of current projects: 1. Durham South; 2. Durham North (of which this report summarises the results); 3. Permian bedrock desk study, including 6 geological cross-sections.

Figures for the report are included in Appendix 1 and paper copies of the cross-sections in Appendix 4. Digital images of cross-sections, both as raw jpeg, TIFF and PDF images and CorelDraw diagrams are supplied separately on the accompanying project delivery CD.

2 Geological Summary

2.1 BACKGROUND

The first stage when constructing cross-sections using GSI3D software (© Insight GmbH) is to set up a generalised vertical section (GVS). To do this a review of existing literature was undertaken. Much of this literature has been summarised in Stone, Millward & Young (In prep.) for the forthcoming BGS British Regional Geology publication for Northern England. The lithostratigraphic summary from this report was used to define the GVS for the Durham superficial deposits study.

Correlation of geological units based on lithostratigraphy was chosen in preference to lithology because it allows a better representation of the glacial geological history and clearly shows packages of sediments that were deposited in specific glacial environments. Two glacigenic subgroups that contain deposits from the two main ice masses that impinged on the study area contain lithostratigraphic units that equate to each other in terms of time and method of deposition (see Table 1). Equivalent units were placed adjacent to each other in the GVS column. This summary and comparison of glacigenic subgroups has helped to condense a large amount of diverse data for this area and the resulting geological cross-sections provide the best and clearest summary to date of the regional superficial geology.

	North Pennine Glacigenic Subgroup	**North Sea Coast Glacigenic Subgroup**
Late Devensian	Ebchester Sand and Gravel Formation	Fulwell Hill Sand and Gravel (not present in study area)
	Un-named Morainic deposits	Elwick Moraine Member
	Butterby Till Member	Horden Till Member
	Tyne and Wear Glaciolacustrine Formation	Peterlee Sand Formation
	Wear Till Formation	Blackhall Till Formation
Pre-Late Devensian	Maiden’s Hall Sand and Gravel Formation	

Table 1 Comparison of glacigenic subgroups

2.2 BEDROCK

The bedrock underlying the Darlington, Durham and Sunderland area comprises Permian rocks in the east, which unconformably overlie Carboniferous rocks to the west. The bedrock is simplified for representation in the superficial deposits cross-sections into Magnesian Limestone, Permian Yellow Sands and Carboniferous Coal Measures; the Permian Marls are not present in the Durham North sections. The Magnesian Limestone includes the Raisby, Ford, Roker and

Seaham formations, which are indivisible in most boreholes and comprise dolomitic limestones and dolostones that form the main aquifer bodies in the area. The limestones also include patch and shelf edge reef facies in the Ford Formation. At the base of the Magnesian Limestone sequence there is a thin (less than 2 m) dark grey mudstone called the Marl Slate Formation. This mudstone laps around the Permian Yellow Sands (Yellow Sands Formation) comprising weakly cemented, aeolian sandstones, distributed in ridges that represent buried sand dunes beneath the Magnesian Limestone. The Carboniferous Coal Measures of Westphalian age are dominantly interbedded sandstones and mudstones with coal seams. The Stainmore Formation is not present in the Durham north sections. More complete details of the Permian and Carboniferous sequence will be included in the bedrock-modelling phase of the study (Phase 3).

2.3 SUPERFICIAL DEPOSITS

The superficial deposits consist of glacial and associated glaciolacustrine and glaciofluvial sediments of Late Devensian age overlain by younger Flandrian deposits. The Late Devensian deposits have been divided using the lithostratigraphic nomenclature outlined in Stone, Millward & Young (In Prep.). The sequence of superficial deposits is shown in Table 2. The existing digital 1:50 000 geological superficial geology map is shown in Figure 1 and geological cross-sections referred to in the text are provided in Appendix 4. Digital versions of the cross-sections are included on the accompanying CD.

The Late Devensian deposits rest predominantly on bedrock. The bedrock surface represents a pre-Devensian erosion surface, into which several buried channels, mostly of east-west orientation, up to 80m deep, were cut and later filled during the early stages of the Late Devensian glaciation. During the glaciation, ice streamed down the North Sea coast from the Tweed basin and other sources to the north (North Sea Ice Stream). In addition, a number of glaciers flowed across the area from the west, bringing ice from the Southern Uplands and Lake District across the Tyne and Stainmore Gaps respectively (North Pennine Ice Sheet). Local ice centres were also present, but probably cold-based and non-erosive, over the higher ground in the North Pennines and Cheviots (Stone, Millward & Young, In Prep.).

Superficial deposits of Late Devensian age in the study area demonstrate the interaction of the two main ice masses, the offshore (North Sea) and onshore (North Pennine) ice. Consequently the Late Devensian deposits are classified into two Glacigenic Subgroups. Sediments sourced from the North Sea ice are classified under the **North Sea Coast Glacigenic Subgroup,** and those sourced from the North Pennine ice are in the **North Pennine Glacigenic Subgroup**. The boundary between the two subgroups occurs at the western-most edge of North Sea ice encroachment, which is marked by the presence of the Elwick Moraine Member between Sheraton and Elwick, and in the area around Darlington. The North Pennine Glacigenic Subgroup occurs predominantly to the west of this ice limit, with the North Sea Coast Glacigenic Subgroup predominantly on the eastern (coastal) side. The approximate margin of the North Sea ice is shown in Figure 2.

The two glacigenic subgroups contain a similar, ‘tripartite’ sequence of sediments, broadly consisting of lower and upper tills separated by an intervening glaciolacustrine, or in some places glaciofluvial, unit. This ‘tripartite’ sediment sequence has been interpreted as evidence for a period of ice advance in the Late Devensian, which deposited the basal tills, followed by a partial retreat of the onshore ice mass, during which a separation or period of buoyancy of the North Pennine ice and North Sea ice occurred. During this time a large, glacial lake system “Glacial Lake Wear” developed as rivers carrying water from the retreating North Pennine ice mass in the west were dammed up against the North Sea ice that remained along the coastal region (Figure 2). At this same time subglacial channels were cut in tunnel valleys beneath the two main ice sheets and filled with glaciofluvial, glaciolacustrine and deformation tills where ice partially readvanced or resettled after a period of buoyancy. The channels tend to be parallel to the direction of the ice flow in a northeast-southwest or northwest-southeast orientation. The upper till units were deposited during a later ice re-advance over the area following deposition of these glaciolacustrine, glaciofluvial and deformation till sediments in the buried channels (Stone, Millward & Young, In Prep.).

Table 2 Stratigraphy of superficial deposits

Age	Generic Name	Litostratigraphic Name*	Thickness	Description	Glacigenic Subgroup
Recent	Made ground	Made ground (18)	0-10 m	Anthropogenic deposits.	
Flandrian	Marine deposits	Marine deposits (17)	0-5 m	Sand and gravel.	
	River Terrace Deposits	River Terrace Deposits (16)	0-10 m	Sand and sand and gravel terraces	
	Alluvium	Alluvium (15)	0-10 m	Interbedded sand, sand and gravel and silty clay in active river channels.	
	Peat	Peat (14)	>1 m	Peat.	
	Lacustrine deposits	Lacustrine deposits (13)	0-20 m	Soft to firm lacustrine clay, silt and sand. Some peat horizons.	
	Tidal flat deposits	Tidal flat deposits (12)	0-5 m	Sandy, silty clay.	
	Raised marine deposits	Raised marine deposits (11)	0-2 m	Thin and patchy clay and sand deposited on a marine terrace cut into superficial deposits.	
Late Devensian	Glaciofluvial sand and gravel	Ebchester Sand and Gravel Formation (10)	0-20 m	Glaciofluvial sand and gravel lying in isolated mounds or forming terraces on valley sides.	North Pennine
	Ice marginal diamictons and rafted till	un-named moraine (9)	0-5 m	Clay with boulders and gravel.	North Pennine
		Elwick Moraine Member (8)	0-5 m	Moundy deposits of sand and gravel containing shell fragments, sand, contorted silts, clays and pebbly clay diamictons. Locally comprises mostly till in push moraines.	North Sea Coast
	Upper deformation tills	Horden Till Formation (7)	min 2-10 m	Brown or red-brown clay with gravel. Stiff, contains a relatively high proportion of clasts of Upper Magnesian Limestone.	North Sea Coast
		Butterby Till Member (6)	min 2-20 m	Silty to sandy clay, stiff, reddish brown to brown, with sparse to abundant gravel. (Includes Pelaw Clay Member of Smith (1994)).	North Pennine
	Glaciofluvial and Glaciolacustrine Deposits	Peterlee Sand Formation (5)	min 0-15 m	Glaciofluvial sand, silt and clay, commonly coarsening upwards to gravel but within buried valleys locally comprised of up to 30m laminated clay.	North Sea Coast
		Tyne and Wear Glaciolacustrine Formation (4)	up to 50 m	Lacustrine clay and sandy/silty clay with lenses of sand, sand and gravel, and thin interbedded tills. In some areas sand and gravel dominates.	North Pennine
	Lower lodgement tills	Blackhall Till Formation (3)	up to 35 m	Silty clay with sand, gravel and cobbles. Grey to brown.	North Sea Coast
		Wear Till Formation (2)	up to 60 m	Silty or sandy clay with gravel, cobbles and/or boulders. Firm to stiff, extremely consolidated, stony, brown/blue with lenses of clay, silty clay, sand and sand and gravel.	North Pennine
	Basal sand and gravel	Maiden's Hall Sand and Gravel Formation (1)	up to 10 m	Sand or sand and gravel filling buried valleys in the bedrock.	North Pennine

Numbers in table refer to description of units within text and cross-section diagrams for clarity

2.3.1 Rockhead and Buried Channels

In the area between Durham and Sunderland the Permian escarpment forms a distinctive north-south trending topographic 'high' with very little cover of superficial deposits. Rockhead elevation falls steeply to the west of the escarpment where there is a thin cover of superficial deposits. The bedrock surface drops in height more gently to the east of the escarpment and the superficial deposits thicken slightly towards the coast. A topographic depression in the Sunderland area, where rockhead drops to several metres below sea level corresponds with an extensive development of glaciolacustrine deposits underlain by lower till.

A number of channels have been cut into the bedrock surface at least two stages in the glacial history of the area. Early (Pre-Devensian) channels generally trend east-west and later (possibly Devensian) channels trend generally northwest-southeast or northeast-southwest. These channels are up to 50 m deep and are filled with the complex sequences of clay, sand and gravel and diamictons of the Tyne and Wear Glaciolacustrine Formation (see section 2.3.3) underlain by the lower till. Notable channels are seen in cross-sections DN_3 near Easington, DN_2 near Butterwick Moor and in the eastern half of DN_5.

2.3.2 Late Devensian deposits: Lower tills

The lower till units rest directly on bedrock, or locally on isolated pockets of sand and gravel that occupy hollows in the bedrock surface. This basal sand and gravel unit is the **Maiden’s Hall Sand and Gravel Formation** (1). A 12 m thick deposit of sand beneath the lower till in at the western end of DN_5, near Bowburn is the Maiden’s Hall Sand and Gravel Formation. The lower tills are extremely consolidated lodgement tills, formed beneath flowing glacial ice, and contain many clasts of varying sizes in a matrix of clay and silty clay.

In the area to the west of the North Sea Ice limit the lowest till unit is called the **Wear Till Formation** (2) (North Pennine Glacigenic Subgroup). It consists of blue to brown silty or sandy clay with gravel, cobbles and sporadic boulders. Clasts comprise mainly Carboniferous sandstones and mudstone with some coal, together with Whin Sill dolerite and erratics of igneous rocks from the Lake District and southern Scotland. Magnesian Limestone clasts are abundant where the Wear Till Formation overlies it. It also contains some lenses of clay, silty clay, sand and sand and gravel. The maximum thickness of the Wear Till Formation in the Durham North cross-sections is about 30 m.

Along the Durham coast to the east of the North Sea Ice limit, the basal till is the **Blackhall Till Formation** (3). This is a stiff, grey to brown silty clay with sand, gravel, cobbles and shell fragments. Clasts of Carboniferous sandstone, mudstone, limestone and coal are present along with rocks from the Southern Uplands and some local Permian lithologies south of the Tyne.

2.3.3 Late Devensian deposits: Glaciofluvial and glaciolacustrine sediments

Lying stratigraphically between the lower and upper till units is a complex sequence of glaciolacustrine sediments. To the west of the Permian escarpment these sediments rest predominantly on bedrock. These may be up to 40 m thick in buried valleys and up to 30 m thick in other areas. The sediments, termed the **Tyne and Wear Glaciolacustrine Formation** (4), consist largely of brownish-grey clay and silty or sandy clay, which is frequently laminated. Isolated lenses or pockets of sand or sand and gravel may be present within the clay. In section DN_1, near Middle Herrington [NZ 3550 5350], the unit consists largely of sand and gravel, sand and sandy silt with some thin diamictons. This complex sequence was deposited in “Glacial Lake Wear”, “Glacial Lake Edderacres” and associated lake basins (Figure 1), during a period of ice retreat in the Late Devensian glaciation.

To the east of the North Sea ice limit, the predominantly glaciofluvial deposits of the **Peterlee Sand Formation** (5) overly the lower till units (DN_7 near Burdon) and, in places, the Tyne and Wear Glaciolacustrine Formation (where DN_3 crosses DN_8 at Ryhope). The Peterlee Sand Formation is predominantly sandy and may be cross-bedded, in some areas the unit may be gravely.

2.3.4 Late Devensian deposits: Upper tills

The upper till units overly the glaciofluvial and glaciolacustrine sediments in many areas, and sometimes rest directly on the lower till. These upper tills contain fewer clasts than the lower tills, are less consolidated and in many areas consist largely of clay. This has lead to a variety of interpretations, including the suggestion that they may be weathered surfaces of the underlying till or some other deposit. In this project the definitions from Stone, Millward & Young (In Prep.) have been used. They interpreted the units as deformation tills formed by ice moving over soft, deformable beds and typically containing very dispersed clasts. In places these upper tills and till lenses within the Tyne and Wear Glaciolacustrine Formation can be seen to overlie deformed glaciolacustrine deposits, for example, in sections at Maiden's Hall opencast quarry, north of Morpeth (Merritt, J W. Pers. Com.).

The upper till in the east of the area is the **Horden Till Formation** (7) (North Sea Coast Glacigenic Subgroup), a brown to red-brown clay with gravel, usually 2-10 m thick. Compared with the lower till in the area, the Horden Till Formation contains a relatively higher proportion of clasts derived from the upper parts of the Permian Limestone, the overlying sedimentary rocks, and volcanic rocks derived from the Cheviot area.

To the west, the upper till of the North Pennine Glacigenic Subgroup is the **Butterby Till Member** (6). It is less compact and stony than the underlying Wear Till Formation, but contains a similar suite of clasts. The unit previously described as the Pelaw Clay, which overlies most of the glaciolacustrine sediments in the Tyne-Wear area (Smith, 1994 and BGS 1:50 000 sheet 21 Sunderland) has been included in the Butterby Till Member. The maximum thickness of the Butterby Till Member is 20 m but it is most commonly between 2 and 15 m thick.

2.3.5 Late Devensian deposits: Late glacial ice marginal and glaciofluvial sediments

Moundy deposits of sand and gravel and diamictons (unsorted gravel and cobbles in a silty clay matrix) occur in the area between Easington and Elwick and to the eastern side of Darlington. These have been interpreted as ice-marginal deposits and grouped as the **Elwick Moraine Member** (8). A few moundy diamicton deposits are widely dispersed to the west of the main belt of the Elwick Moraine Member and have been also been classified as moraine, but have no lithostratigraphic name assigned (9).

Sand and gravel in mounds or terraces along valley sides form the **Ebchester Sand and Gravel Formation** (10). These are the product of glaciofluvial reworking of deposits left by retreating ice during the final deglaciation of the area.

2.3.6 Post-Glacial deposits

Raised Marine Deposits (11) occur in the region around Hartlepool. A raised marine terrace is present, cut into the superficial deposits to the west and south of Hartlepool docks as shown in section DN_6. The terrace is essentially an erosional feature, cut into Magnesian Limestone at West Hartlepool and into superficial deposits elsewhere. Patchy marine deposits are present on the terrace, up to a maximum thickness of about 1 m, and comprise mostly reworked material from the underlying deposits. A raised storm beach can be found at the landward edge of the terrace at West Hartlepool, but this is not encountered in the cross-sections of the superficial deposits.

Tidal Flat Deposits (12) are present in Hartlepool but do not occur in the Durham North cross-sections.

Lacustrine Deposits (13) consisting of clay and silty clay have formed throughout the Flandrian in small lakes present in isolated hollows and poorly drained areas of the post-glacial superficial deposit surface.

Peat (14) is not present in the Durham North cross-sections.

The most extensive deposits of **Alluvium** (15) are found in the areas associated with the main drainage courses, especially the River Wear (see for example section DN_9). Small patches of alluvium are found in minor tributary streams throughout the area. The alluvium consists of up to 24 m of sand, gravel and/or clay or silty clay in the valley of the River Wear and 0-5 m in other areas.

River Terrace Deposits (16) do not occur in the Durham North cross-sections.

Marine Deposits (17) occur along the coast near Sunderland and consist mainly of beach material. The deposits are seen at the eastern end of section DN_9.

Made Ground (18) has been included in the cross-sections where it is present in the borehole log. Other types of artificial ground have not been encountered. Made Ground, especially in the first 1-2 m from the ground surface, is likely to be extensive throughout all built-up areas in the region. Older boreholes used to generate the cross-sections will not represent the current extent of Made Ground if significant urban development has occurred since it was drilled.

3 Borehole Coding

Lithological interpretations of boreholes were derived from paper records held within the National Geoscience Data Centre at the British Geological Survey and additional digital records provided by the Environment Agency. Where possible, Environment Agency borehole records were matched with those in the records of the British Geological Survey and the Environment Agency name used in the borehole file. Where no match existed, geological data from the Environment Agency boreholes was entered manually into the project borehole files.

Approximately 1000 boreholes were coded for the northern project area (Figure 3). Other interpreted boreholes within the BGS system were also included, giving a total of about 1200 available for consultation in cross-section construction or borehole queries to calculate thicknesses of main aquitard or aquifer units within the superficial deposits (Figure 4).

3.1 CODING METHODOLOGY

Boreholes were coded according to the description of the down-hole lithology recorded on the paper records of the borehole. The quality of the original description varied according to the age of the record and the purpose for which the borehole was drilled (e.g. site investigation, water abstraction or coal exploration). In addition to lithological interpretation, the appropriate stratigraphic code was applied where the coder was confident of the interpretation. The stratigraphic codes used for the project were derived from the BGS Stratigraphic Lexicon (http://www.bgs.ac.uk/lexicon/lexicon.html).

Sites of all confidential and non-confidential boreholes can be obtained from the BGS website at http://www.bgs.ac.uk/geoindex/home.html

The lithological codes for the superficial deposits were derived from the BGS Superficial Deposits Coding Scheme (Cooper *et al*, 2005). The scheme uses six letters to denote the primary lithology of a deposit and is shown below in Table 3.

Lithological Units	**Code**
Peat	P
Sand	S
Silt	Z
Clay	C
Gravel	V
Cobbles	L
Boulders	B
For Made Ground	FILLU

Table 3 Superficial deposits lithological coding scheme component codes

Where more than one lithological unit is present (for example a sandy clay), the letters can be combined in descending order of importance to reflect the full lithology of the material (for example CS for sandy clay). The coded lithological and stratigraphic information was added to the BGS Borehole Geology database to be retrieved subsequently for correlation.

The location of all non-confidential boreholes (and Environment Agency boreholes) used to create the cross-sections is shown in Figure 5.

3.2 BOREHOLE ELEVATION

Each borehole was referenced to an elevation with respect to Ordnance Datum. The presence of this information on a borehole log was variable. If the elevation was recorded on the borehole log it was used in the database. If the elevation was missing, it was either derived manually from Ordnance Survey contours and spot heights or automatically from the NextMap digital terrain model. Mismatches between DTM and borehole start heights may be due to change in ground conditions since the borehole drill date such as excavations or made ground and inherent errors in the DTM.

4 Cross-Section construction

The locations of the regional cross-sections are shown in Figure 1. In total, 10 cross-sections were constructed and correlated, six east-west and three north-south. This approximates to 181 km of section lines.

4.1 METHODOLOGY

The cross-sections for this study were created using GSI3D (Geological Surveying and Investigation in 3-D) subsurface modelling software (© Insight GmbH). Coded borehole data, digital elevation models, scanned and georegistered map images and digital geological maps were imported and used to define the distribution and geometry of the superficial deposits along the lines of section. The bedrock geology was represented schematically and is subject to a more detailed study in Phase 3 of this study.

A BGS DTM derived from Ordnance Survey Landform Profile data was used to provide the top layer or "cap" to the cross-sections. Coded boreholes were imported into GSI3D from the BGS Borehole Geology database in their correct spatial positions. From the complete database of coded boreholes, the highest quality logs were selected for inclusion in the cross sections. The selection process was based a number of key criteria, including depth (preferably boreholes reaching bedrock) and quality of description.

Each borehole added to the line of section defined a control point for subsequent geological correlation. Approximately 1000 boreholes were coded in the Durham north study area and of these approximately 850 are non-confidential. The deepest boreholes used were over 500 m deep, but the average depth of boreholes was 41 m. The deep holes both on and off the lines of section were used to roughly constrain the geological stratigraphy and thickness of each unit. Lists of the non-confidential boreholes used in each cross-section with their depths, along with co-ordinates of synthetic points where no boreholes are present, are included in Appendix 1. An Excel spreadsheet and GIS shapefile of this borehole information is provided separately on the project delivery CD.

In addition to the BGS held borehole data, EA boreholes were imported and included in the cross-sections where possible. A large number of these boreholes, however, do not lie on or close to the pre-defined section lines and have not been included.

4.2 CORRELATION

Coded boreholes (including lithology and lithostratigraphy) were displayed on screen in GSI3D. These descriptions were used as data-rich anchor points to begin to build the correlation. The geological units correlated along the sections are shown in Table 2.

Existing 1:50 000 scale 2-D digital geological map data (Figure 1) was used to aid correlation and define the limits and relationships of different geological units. Figure 6 shows the cross-sections displayed within GSI3D in 3-D.

The cross-sections intersect data poor and data rich areas. Data rich areas, where the borehole density is high, results in high confidence of the lithostratigraphic correlations. In data poor areas, lines of correlation were projected from data rich areas, or interpreted from an understanding of the local geology. Geological confidence in these areas is lower. Many of the data poor areas result from the presence of underground bores that are unsuitable for inclusion in the project. The underground boreholes were, therefore, not coded for this phase of the study.

5 Hydrogeology and Hydrogeological Domains

For the purposes of this phase of the project, hydrogeological domains within the superficial deposits were identified, at a regional scale from the cross-sections. The domains applied to areas where superficial deposits in the project area are underlain by Permian bedrock comprising the Permian Yellow Sands Formation and Ford, Raisby, Seaham and Roker formations (Magnesian Limestone).

A methodology was developed to derive the hydrogeological domains via a combination of computer queries to analyse lithological borehole data and limited 3-D modelling of units defined as minor aquifers. A summary of the hydrogeology of the project area is given below along with a description of the methodology used to derive the hydrogeological domains.

5.1 OVERVIEW

An early attempt to zone the superficial deposits of the area of the Skerne valley, to the south of the Butterknowle Fault, was made by Cairney and Hamill (1977, 1979). This identified four zones, which have been described below and which are applicable to some the southern parts of the Durham north study area:

a) Relatively thin cover of glacial deposits to the west of the River Skerne.

b) The zone adjacent to and underlying the River Skerne, where the cover is always in excess of 6 m in thickness and comprises stiff grey clay with interbanded silt and sand.

c) To the east of the River Skerne, where the superficial deposits are in excess of 30 m in thickness and acts as an aquitard.

d) An infilled proglacial lake between Bradbury and Preston-le-Skerne, characterised by higher permeability deposits.

This study was primarily derived from engineering properties and is not as extensive as the work that forms the subject of this report.

The hydrogeological domains that form the focus of this model are designed to provide the basis for modelling groundwater recharge to the Magnesian Limestone. This section describes the hydrogeological information that has informed the designation of the hydrogeological domains. The model is based on the initial understanding that the Magnesian Limestone is a major aquifer, which to the east is capped by Permian Marl that causes increasing confinement of the groundwater in the Magnesian Limestone.

5.2 HYDROGEOLOGY OF THE MAGNESIAN LIMESTONE.

A detailed study of the hydrogeology of the Magnesian Limestone is beyond the remit of this project. However it is considered that the following account provides a useful summary of the main concepts that have informed the domain modelling. The hydrogeology is influenced by both the lithology and the structure. Groundwater flow is predominantly within fractures with some intergranular storage, (Brewerton *et al.*, 1997). Characteristically, the Magnesian Limestone is heavily fractured and in the area to the east of Durham cavernous; as a consequence the hydraulic conductivity (and transmissivity) of the limestone is variable.

There is very little published information available with respect to the analysis of core samples, or field-testing; the data that is available confirms the variability in hydrogeological properties, with transmissivities ranging between 2200 m^2/day and 11 m^2/day, (Allen *et al.*, 1997). The highest transmissivity values are associated with fault zones and areas of outcrop that have undergone collapse brecciation due to dissolution of gypsum in the underlying horizons (Dearman and Coffey, 1981). Allen *et al.*, (1997) reported that in areas where the Middle Magnesian Limestone (Ford Formation) or brecciated Upper Magnesian Limestone (Seaham Formation) represents greater than half of the saturated thickness hydraulic conductivities may be greater than 12 m/day.

In the Durham south area, and at the southernmost extremity of the Durham north area, gypsum is present in the Edlington (up to 30 to 40 m of gypsum at the base) and Roxby (approximately 10 m of gypsum towards the base) formations, particularly in the vicinity of Darlington, extending south towards Doncaster (Lamont-Black *et al.*, 2005; Paukštys *et al.*, 1999). South of the Butteknowle Fault (that extends approximately east-west through Hartlepool) the Edlington Formation acts as a leaky aquitard, separating lower (Yellow Sands, Raisby and Ford formations) and upper (Seaham Formation) aquifers (Lamont-Black *et al.*, 2005). North of the Butterknowle Fault the Edlington Formation is largely missing and the evaporites dissolved so that the various limestones sit one on the other. Consequently, it is difficult to separate the Ford, Roker and Seaham formations. Allen *et al.*, (1997) report that the hydraulic conductivity of the Lower Magnesian Limestone aquifer (Raisby Formation) is less than 5 m/day and that there is a variation in hydraulic conductivity with depth, suspected to reflect the presence of more massive and sometimes calcitic beds at the base of the formation.

Recharge areas predominate along the western outcrop of the aquifer; however some recharge also occurs through the superficial deposits, where flow paths associated with surface water sources have developed (Cairney and Hamill, 1977; Hamill, 1980). The regional hydraulic gradient is to the east and southeast (Lamont-Black *et al.*, 2005). Lamont-Black *et al.* (2005) reported that recharge is carried down dip (2-3 degrees), such that an upward head is generated across the gypsum at the base of the Edlington Formation, which drives gypsum dissolution. Groundwater levels determined in nested piezometers installed in boreholes to the southeast of Darlington (Lamont-Black *et al.*, 2005) indicate that groundwater levels in the superficial deposits are higher than those in the solid rock beneath, which is attributed to the low permeability of the superficial deposits and indicates the potential for some recharge. Greater seasonality of groundwater levels was observed in piezometers installed in the solid geology. Various authors, including Brewerton *et al.*, (1997) report that groundwater levels have steadily risen due to changes in pumping regimes and in particular the cessation of pumping in areas of former coal mining. This particularly affects the south-easterly dipping Carboniferous strata exposed to the west of the Magnesian Limestone and dipping beneath it.

Groundwater abstraction from the Wear catchment is managed through the Environment Agency CAMS (Catchment Abstraction Management Strategy) scheme. The CAMS consultation document notes the importance of the Carboniferous strata in providing the baseflow to rivers of the Wear catchment. To the south of the Butterknowle Fault groundwater levels have been recovering following the cessations of minewater pumping and this is known to impact on the quality of groundwater in the Magnesian Limestone (Neymeyer, Williams and Younger, 2007). It is reported that although minewater levels in the Wear CAMS are recovering, they are controlled by Coal Authority pumping at: Horden, Vinovium, Chester South Moor, Kibblesworth and Kimblesworth. The problems of minewater quality (increase in manganese, changes to pH and increases in carbon dioxide) have been considered by a number of authors including Neymeyer, Williams and Younger (2007), Green *et al.* (1999), Neal *et al.* (2000) and Younger (1995). Neal *et al.*, (2000) also considered the influences of historic lead-zinc mining, dispersed contaminants such as pesticides and sewage inputs on the quality of the River Wear.

5.3 HYDROGEOLOGICAL DOMAIN MAPPING

Domain mapping, as a tool for use in the context of assessing both aquifer recharge (McMillan *et al.*, 2000) and aquifer vulnerability (Dochartaigh *et al.*, 2005), is well established. Quaternary sediments are characterised by variable and complex lithologies, with variable structure and are important for determining the amount of water that will recharge the deeper groundwater system. Clearly, this needs to be considered in the context of the head distribution and topography, as defined in the conceptual model and referred to above. Notwithstanding this, the principle of domain mapping is the recognition of sequences of lithologies that are characterised by similar hydrogeological properties.

Domains are used to reduce the complexity of the superficial deposits for the purposes of understanding the recharge processes better. The lithostratigraphical units are grouped according to how the superficial sequence will affect groundwater flow between the limestone aquifers and the ground surface.

The domains that form the subject of this report have been scheduled from an assessment of the permeability of the superficial deposits (as described and coded within borehole records) and their distribution on the sections. Many of the units are thin, which reduces their hydrological effectiveness. Accordingly, it is necessary to apply thickness criteria in the scheduling of the domains. Thus, following consultation with the Environment Agency, the domains were further subdivided to reflect the variability in the thickness of the low permeability strata, essentially the tills and glaciolacustrine deposits. The schedule of hydrogeological domains that resulted from this assessment is shown in Table 4.

The poorest representation in the domains is that of the Tyne and Wear Glaciolacustrine Formation (named the Middle Sands in Smith and Francis (1967)). This is because the deposits are generally not laterally continuous, often forming isolated mounds, as described above. Locally they are likely to be water-bearing and where they occupy buried channels there is a potential for them to form groundwater flow paths. For this reason the buried channels have been presented as an additional domain.

Once the domains had been scheduled, the mechanism of their derivation comprised the calculation of total continuous aquifer and aquitard thicknesses for the grid of boreholes using the programming function within Map Info (Section 5.4), correlation with the sections and limited use of 3-D modelling within GSI3D (Section 5.5).

Table 4 Hydrogeological domains for Durham North

Hydrogeological Domain	Characteristics	Notes on Lithostratigraphical units
1	> 30 m aquitard over bedrock aquifer	Aquitards: till (Weardale and Butterby) and/ or glaciolacustrine deposits
2	10–30 m aquitard over bedrock aquifer	Aquitards: till (Weardale and Butterby) and/ or glaciolacustrine deposits
3	10–30 m aquitard over > 5 m of minor aquifer over bedrock aquifer	Aquitards: till (Weardale and Butterby) and/ or glaciolacustrine deposits Minor Aquifer: Maiden's Hall Sand and Gravel
4	>5 m minor aquifer over 10–30 m aquitard, over bedrock aquifer	Minor aquifers: Alluvium, Ebchester Sand and Gravel, Peterlee Sand Formation, Alluvial Terrace deposits and Sand and Gravel of Tyne and Wear Glaciolacustrine Formation (at surface) Aquitards: as defined above
5	5-10 m aquitard over bedrock aquifer	Aquitards: as defined above
6	5–10 m aquitard over > 5m minor aquifer over	Aquitards: as defined above

Hydrogeological Domain	Characteristics	Notes on Lithostratigraphical units
	bedrock aquifer	Minor aquifer: Maiden's Hall Sand and Gravel
7	> 5 m minor aquifer over 5–10 m of aquitard over bedrock aquifer	Minor aquifers: Alluvium, Ebchester Sand and Gravel, Peterlee Sand Formation, Alluvial Terrace deposits and Sand and Gravel of Tyne and Wear Glaciolacustrine Formation (at surface) Aquitards: as defined above
8	> 5 m minor aquifer over > 30 m aquitard over bedrock aquifer	Minor aquifers: as defined above Aquitards: as defined above
9	>5 m of minor aquifer over <5 m aquitard over bedrock aquifer	Minor aquifers: as defined above Aquitards: as defined above
10	<5 m of minor aquifer or aquitard over bedrock aquifer	Minor aquifers: as defined above Aquitards: as defined above
11	Channel deposits	Geographic area of probable buried channels. Regional scale only

5.4 CALCULATION OF HYDROGEOLOGICAL DOMAINS 1

The hydrogeological domains were derived in three stages. During the first stage, all interpreted and coded boreholes available within the project area were classified as an aquifer (permeable) or aquitard (weakly permeable) based on their lithology. Boreholes used included those coded for the project and other coded borehole data within the BGS Borehole Geology database. Every lithological combination within boreholes extracted for use in the project was selected and assigned an aquifer or aquitard classification. In general, sand or gravel dominated units are classified as aquifer and clay or silt dominated units are classified as aquitard. Made, or artificial ground falls within the aquifer classification.

A series of database queries were designed to extract the attributed borehole data and calculate the total net thickness of superficial deposits classified as aquifer or aquitard within each borehole. The total thickness calculation sums the thickness of each separate aquifer or aquitard unit. In addition, the greatest continuous thickness of superficial deposits classified as aquifer or aquitard was calculated. In the latter case, the resulting calculation shows areas where there is thick continuous aquifer or aquitard, not separated by other units. The methodology for producing the borehole data extraction and query is described below:

1. The models represent a mathematical interpolation of BGS' legacy borehole and map datasets including new data supplied for this project by the EA. No third party data relating to Quaternary deposits have been used. A mathematical model does not take into account any conceptual modelling of the form of the superficial deposits.
2. The 'Natural Neighbour' modelling used with this data provides a smoothed, average-fit surface. Alternative modelling techniques will generate alternative models (see below).

3. The borehole data used to make the models are subject to a small degree of error; new borehole data lodged with BGS Offices in recent months may not have been incorporated within the models.
4. The map data used to make the models are based upon DigMapGB50 Version 3.14.
5. The models provide indicative values of thickness and elevation and not definitive values.
6. Some borehole logs do not record any geological description within the superficial deposits. In these cases, an aquifer or aquitard classification cannot be applied. The borehole queries would regard these borehole entries as "null" values. Where null values form greater than 20% of the geological record the entire log was excluded from the calculation. This prevents incorrect values representing 0 m thickness of aquifer or aquitard being produced in the final thickness maps.

5.4.1 Gridding details

1. Grids are created using Vertical Mapper and MapInfo V8. Interpolation between data points is via Natural Neighbour analysis i.e. each expected grid value is calculated by area weighting the Voronoi neighbourhood of the nearest surrounding data points.
2. The grids are generated with a cell spacing of 25 m by 25 m, and data are aggregated by a 25 m radius (i.e. points located a cell spacing from their neighbours are averaged).
3. Grids are smoothed (Hermitian smoothing) with local minima and maxima honoured but extrapolation beyond these values is limited.
4. Grids are nulled where DigmapGB50 indicates no superficial material to be present.
5. Gridding of data is iterative. Initially only boreholes proving the whole superficial thickness are processed; boreholes that terminate within the deposits are subsequently added where interpolation indicates they will affect the model (this provides a 'minimum thickness model and is useful in areas of low borehole density).

It is important to understand that this phase of the hydrogeological domains production was calculated from a series of database queries of the classified borehole lithological data only. The use of additional quantitative permeability data, although potentially valuable was beyond the scope of a regional hydrogeological domains study. The thematic maps that were produced during this first phase of hydrogeological domains calculation are shown in Appendix 3.

5.5 CALCULATION OF HYDROGEOLOGICAL DOMAINS 2

The second phase of the production of hydrogeological domains involved 3-D modelling of the thickness and distribution of units classified as minor aquifer in Table 4. The regional cross-sections have shown that, in general, a major aquitard unit in the superficial deposits is represented by glacial till or glaciolacustrine deposits. In some areas, these deposits are either underlain or overlain by units classified as minor aquifers in Table 4. The underlying minor aquifer is represented by the Maiden's Hall Sand and Gravel. The overlying minor aquifer is represented by a combination of Alluvium, Alluvial Terrace deposits, Ebchester Sand and Gravel and Sand and Gravel of the Tyne and Wear Glaciolacustrine Formation where these deposits occur at the surface and are shown on the existing geological map.

For the calculation of the hydrogeological domains, the estimated surface and subsurface distribution of each minor aquifer unit was defined from the regional cross-sections and "helper" sections within GSI3D. Helper sections provide a means of using additional borehole data and interpreted thicknesses constrained by correlation lines on the cross-sections, to model each geological unit. In total, 63 helper sections were used to define the distribution and thickness of all minor aquifers within the project area.

The thicknesses calculated from this process were exported digitally as ASCII grids with a 25 m cell size and converted to ESRI grids for use in the GIS calculation of the hydrogeological domains. The BGS Landform Profile DTM derived from OS data used as a top, capping surface for the calculation had a 50 m cell size.

5.6 CALCULATION OF HYDROGEOLOGICAL DOMAINS 3

The third and final stage of producing the hydrogeological domains involved combining the results from stages 1 and 2 and applying a series of GIS spatial queries to query and combine the digital grids. The grids and contours defined in Section 5.5 (from borehole analysis) were queried against the grids and contours defined in Section 5.6 (from limited 3-D modelling of those deposits identified as potential minor aquifers). In all cases, the domains were applied to areas where superficial deposits are underlain by Permian bedrock comprising the Permian Yellow Sands Formation, Ford, Raisby, Roker and Seaham Formations (Magnesian Limestone), Edlington and Roxby Formations (Permian Marls). The hydrogeological properties of bedrock units were not considered in the definition of the hydrogeological domains.

In addition, the extent of Domain 11 was digitised based on regional analysis of the cross-sections of the probable location of infilled Pre-Devensian and Devensian buried valleys. Their exact geometry and location is not defined, but Domain 11 is included to highlight the potential area affected by these buried valleys where deposits may be more sandy and variable. The hydrogeological domains are presented in Figure 7.

6 Limitations

6.1 BOREHOLE DATA

- Approximately 1000 boreholes were coded for the northern project area. Other interpreted boreholes within the BGS system were also included giving a total of about 1200. A large number of the boreholes were either of poor quality, very shallow, or inadequately logged. Also many underground boreholes exist in this area and are of no use in the superficial geological study. The borehole distribution was uneven, leaving some areas with poor data coverage. As a result, some parts of the interpretation are fairly well constrained and others are less certain.
- Many of the shallow boreholes do not encounter bedrock. Rockhead is constrained by those boreholes that did encounter bedrock, and by reference to a BGS rockhead elevation model.

6.2 GEOLOGICAL INTERPRETATION

- The superficial geology of the study area is complex, and there have been very few detailed studies defining the relationships of the geological units. This project provides a 2-D interpretation of the geology along section lines. Extrapolation between cross-sections will not provide a 3-D geological interpretation. Further detailed borehole analysis and GSI3D modelling would be required if a full 3-D hydrogeological study is intended. A key example is the large number of buried channels described in the literature for the study area. A small number of these are represented in the Durham north cross-sections. A full 3-D geological study would be needed to produce an accurate representation of this complicated network of channels and their lithological variability.

- Boreholes that penetrate the buried valleys exhibit many geological variations. Time limitations on the project allowed only limited subdivision of the buried channel deposits. Some till lenses and sand lenses were identified but not correlated. Further study would allow a more comprehensive interpretation of these complex deposits, which may be extensive lateral conduits of groundwater.
- Cross-section interpretations are based on lithostratigraphy. The geological maps used to aid interpretation are based on lithology and depositional environment. Consequently, the two cannot be directly compared. Undifferentiated glacial sand and gravel deposits shown on the maps are a key example of this. In the cross-section they may be classified as the Ebchester Sand and Gravel Formation or as part of the Tyne and Wear Glaciolacustrine Formation.
- Bedrock is depicted schematically in the cross-sections and divided into representative geological categories to represent the bedrock geology present beneath superficial deposits. No detail in relation to structural dip or exact borehole correlations is intended for this part of the study. Faults are not modelled, but are schematically represented as steep geological boundaries where contrasting units are juxtaposed.

6.3 CROSS-SECTION CONSTRUCTION

- Cross-section interpretation was based on BGS borehole data, EA borehole data, BGS DIGMAP 1:50 000 (Superficial Deposits and Bedrock), BGS rockhead model, published BGS geological maps, published literature and unpublished BGS reports. An OS Profile 1:50 000 Digital Terrain Model (DTM) was used.
- The interpreted cross-section lines closely follow the original sections defined in the project outline. However, some deviation has been necessary due a lack of borehole data along these proposed lines. The cross-sections were created by selecting the best quality boreholes within a buffer zone of 200 m – 300 m of the proposed lines, and by including as many EA boreholes that were within a reasonable distance of the line as possible.
- Correlation lines were drawn based on our own lithostratigraphic interpretation of the borehole data.
- The geological model is defined by cross-section only. No borehole analysis was carried out beyond the cross-sections, other than their lithological interpretation used in the derivation of hydrogeological domains.
- Significant areas of made ground have been identified on the Durham north cross-sections (e.g. 440681 546696, section DN_4). The made ground has been classified as aquifer in the aquifer/aquitard classification of the boreholes (section 5.4). However, it has not been possible to define the wider distribution of made ground and other artificial deposits beyond the cross-sections. Consequently, made ground has not been included in the classification of minor aquifer as defined in section 5.5.

6.4 UNCERTAINTY

Factors contributing to the uncertainty of the geological cross-sections include:

- Borehole data quality
- Borehole distribution (parts of cross-section had limited amounts of data)
- Geological complexity

- Poorly defined pre-existing lithostratigraphy for the area

Factors contributing to the uncertainty of the production of the second phase of the hydrogeological domains include:

- The hydrogeological domains were identified from those relationships within the superficial deposits identified from the regional cross-sections only and where a thick aquitard was overlain or underlain by a minor aquifer. This is appropriate for the scope of the project and should only be used in conjunction with other regional studies. Other, more detailed hydrogeological domains with more complex spatial relationships may exist (such as interbedded sand units within Till or Glaciolacustrine deposits) but it was beyond the scope and methodology of this phase of the project to apply them to the hydrogeological domains. Such domains can only be derived efficiently and effectively by using a 3-D geological modelling approach.
- The helper sections that were used to constrain the thickness and distribution of the overlying and underlying aquifers are generally poorly constrained away from the cross-sections. Where possible, additional boreholes were used, but a detailed analysis of all boreholes was not possible within the resources of the project.
- The spatial relationships derived from the GIS queries within the hydrogeological domains are based on the assumption that in all cases, the Maiden's Hall Sand and Gravel underlies the area of continuous aquitard and that the Alluvium, Alluvial Terraces, Ebchester Sand and Gravel and other glaciofluvial sand and gravel deposits overlie it. The presence and nature of other potential stratigraphical relationships cannot be identified using the methodology described here. The production of the 3-D distribution of the top and base elevation and thickness of each geological unit interpreted from a 3-D geological model would be required.
- In defining the distribution of the superficial deposits classified as minor aquifers, only the larger areas shown on the geological map were selected for inclusion. Small or thin areas that were beyond the resolution of the regional study were not included. This process was based on an assessment of the areas most likely to be significant in the application of the hydrogeological domains.

6.5 RECOMMENDATIONS

6.5.1 Geological

- The geological interpretation is consistent with the regional scope of the study as defined in the project specification. The results of the regional study should not be used for detailed (e.g. site specific) study where additional geological or hydrogeological interpretation may be necessary.
- We recommend a full 3-D geological modelling study to fully understand the spatial relationships and associated 3-D hydrogeological properties and domains within the superficial deposits. This would address many of the limitations discussed in the above sections.

6.5.2 Hydrogeological

- It is important to note that the borehole queries used for the first phase of the production of the hydrogeological domains do not assess the spatial relationships of aquifer or aquitard units within the borehole, only thickness. Consequently, it is not possible to assess from this query whether an aquifer overlies an aquitard, an aquitard overlies an aquifer or whether the two are interbedded. It would only be possible to assess the spatial relationships fully in 3-D by building an attributed 3-D geological model.

- Where “null” values occur in the borehole queries (Section 5.5) and have been excluded, 3-D modelling and cross-section construction would allow the geologist to assess these null values in relation to surrounding boreholes. Consequently, the modeller would be able to assess the probable stratigraphy and resulting hydrogeological properties as part of the 3-D modelling process.
- Although beyond the scope of this project, layers to show groundwater contours (as discussed with the client) would be of benefit to the model.
- Dissolution features (as discussed with the client) would be a potentially useful addition to the hydrogeological model, but was beyond the scope of this project. For example Smith and Francis (1967) make reference to a swallow hole at NZ 2952 2912. It would be possible to generate layers to show dissolution features by adding data from the BGS karst database.
- Consider potential recharge associated with quarry locations as discussed with Environment Agency during the project.
- Thicker deposits of made ground have been encountered in the Durham North sections than were encountered in Durham South. The classification and distribution of Made Ground and other types of artificial ground would be of benefit to the understanding of their hydrogeological significance within the hydrogeological domains.

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Appendix 1 Figures

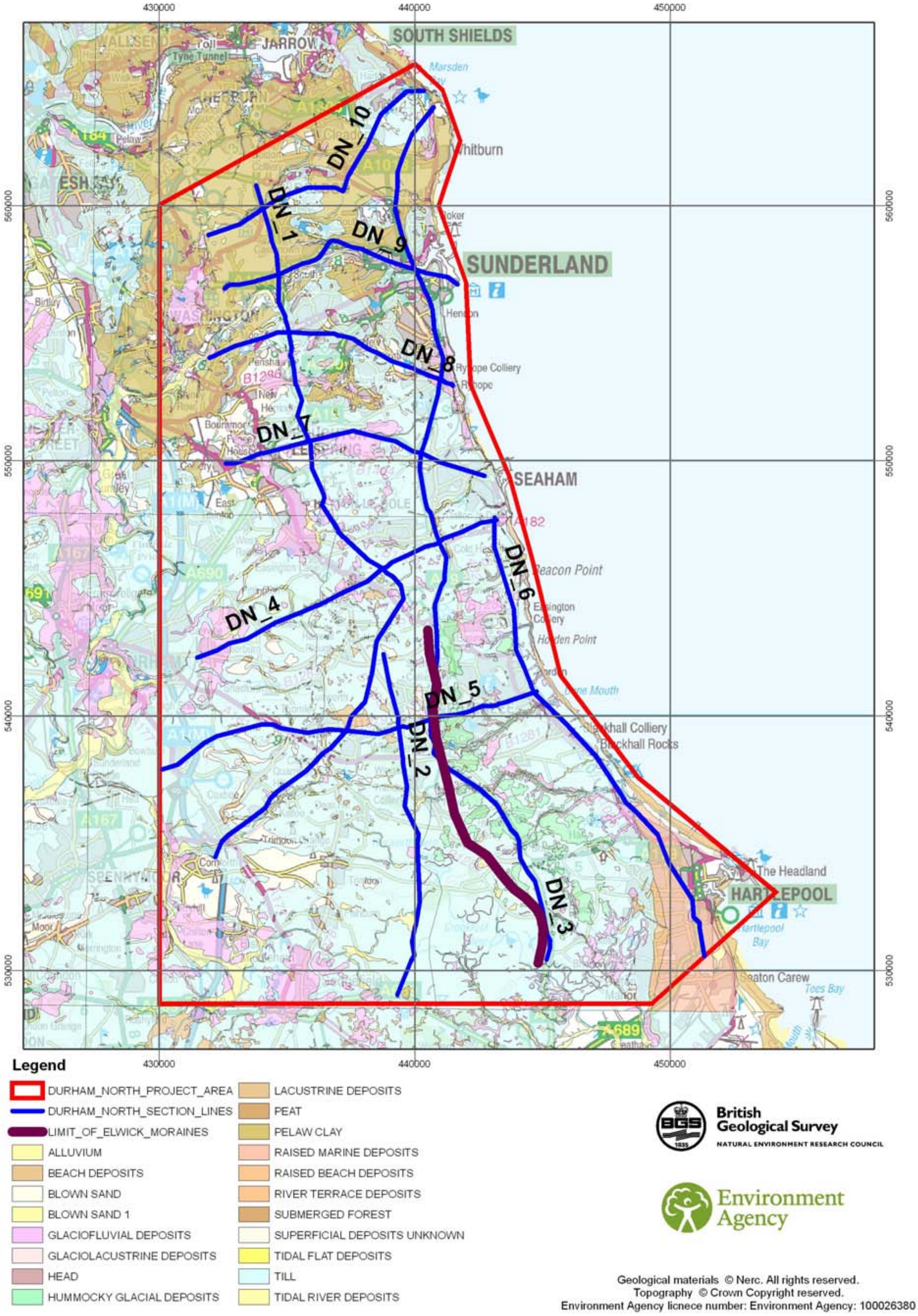


Figure 1 Existing Superficial Deposits map (DiGMapGB 50) of the Durham North area

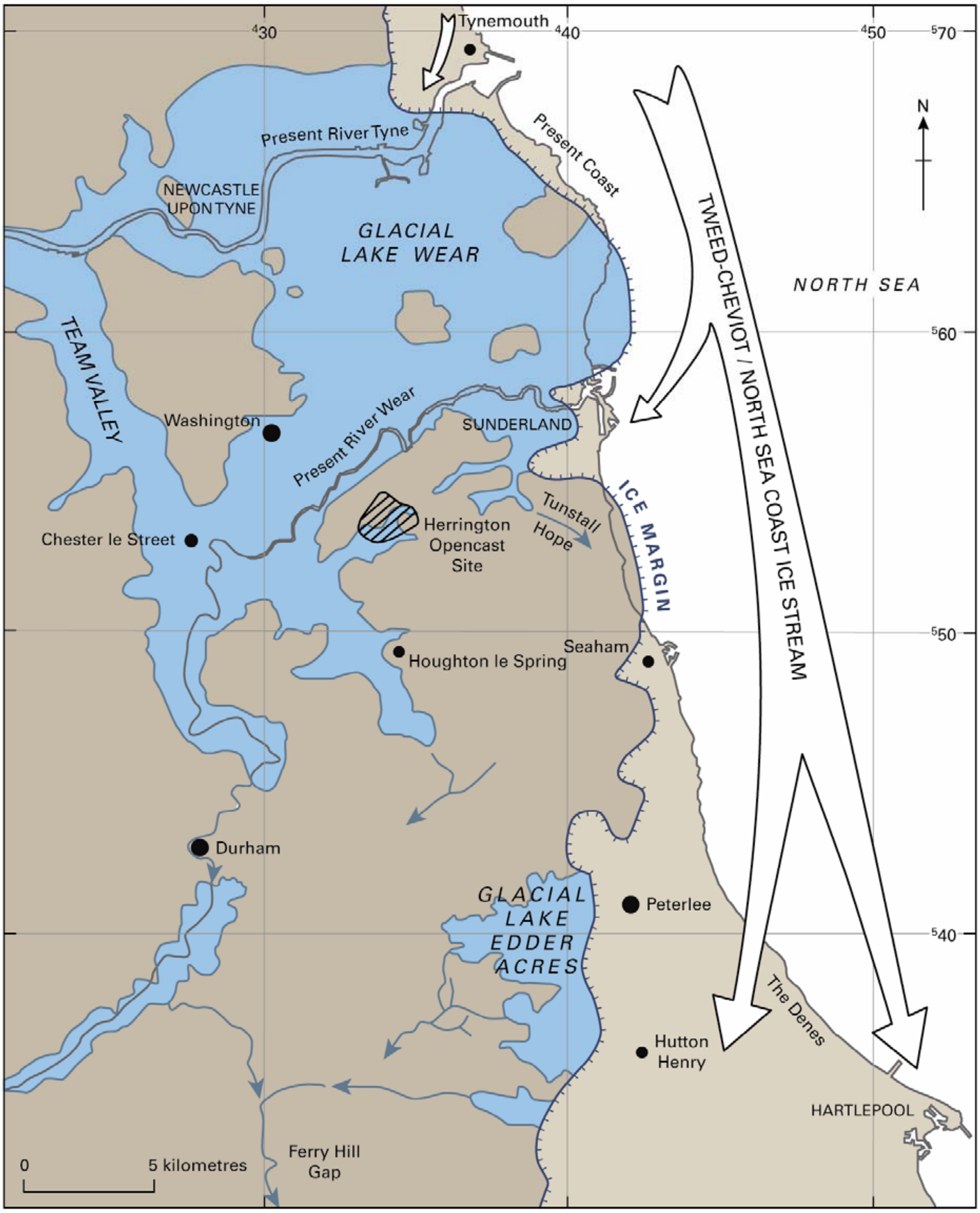


Figure 2 Glacial Lake development in the Late Devensian (Stone, Millward & Young, In Prep.)

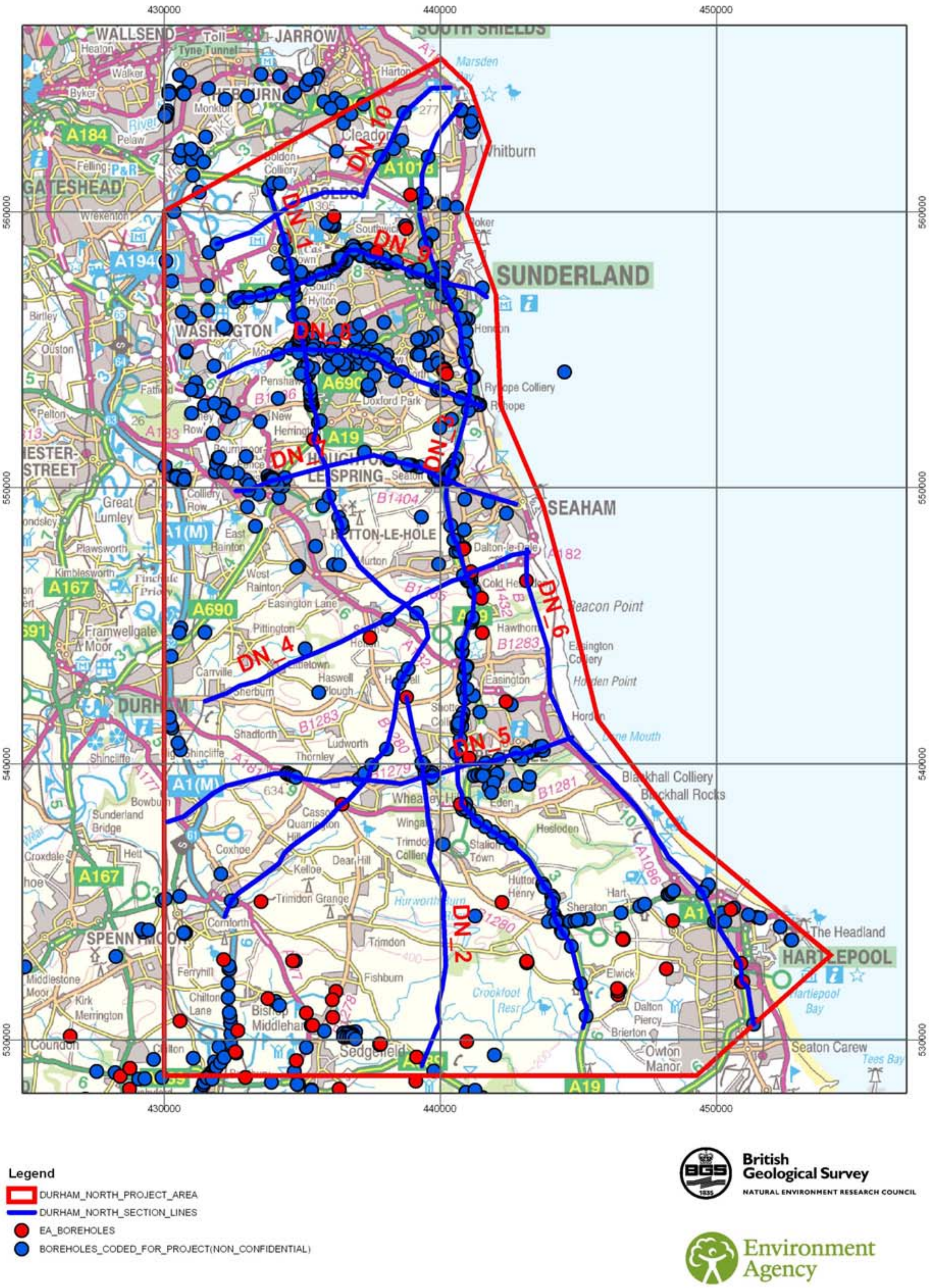


Figure 3 All boreholes coded or provided (from EA) in Durham North region

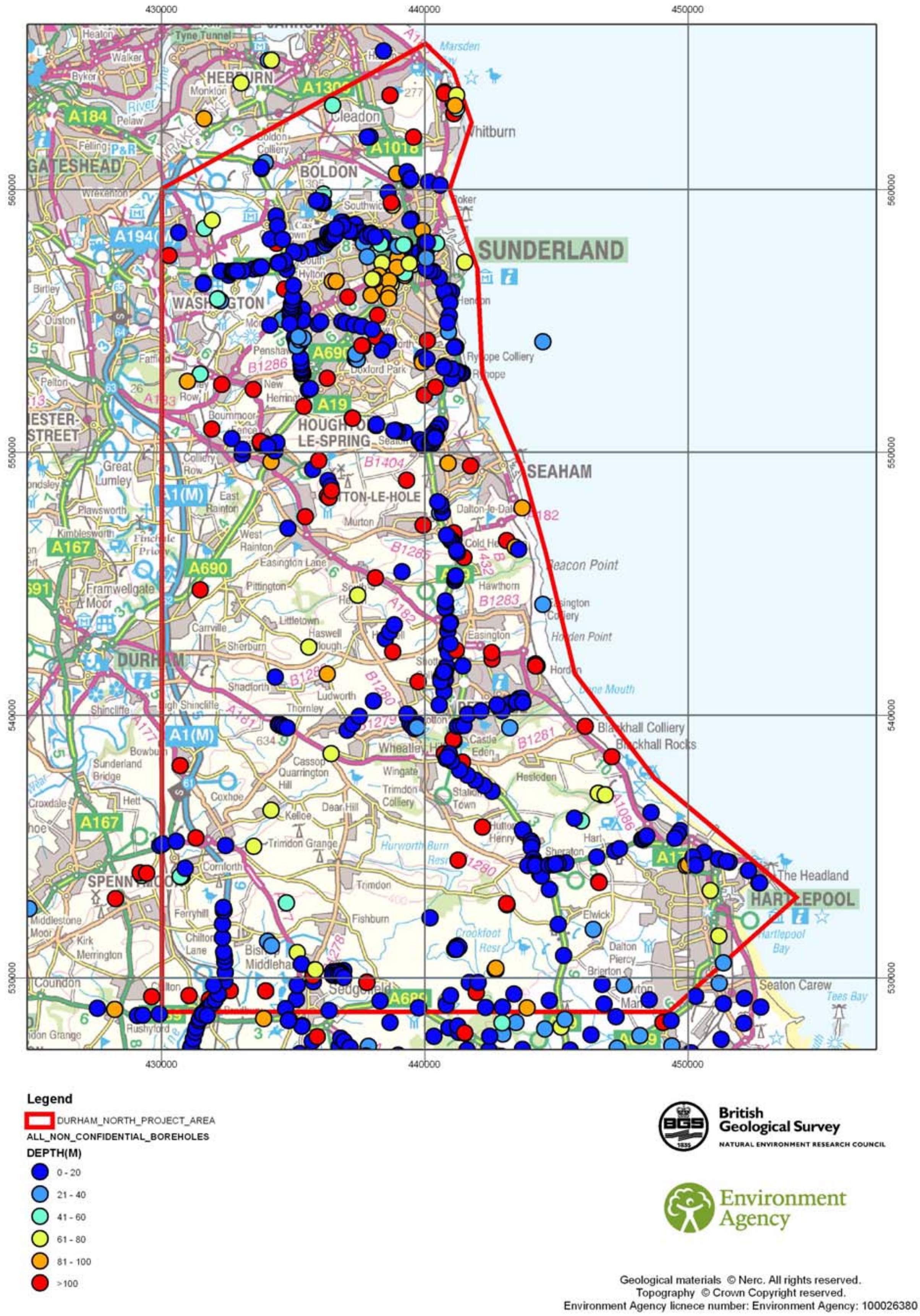


Figure 4 All interpreted non-confidential boreholes available within Durham North region

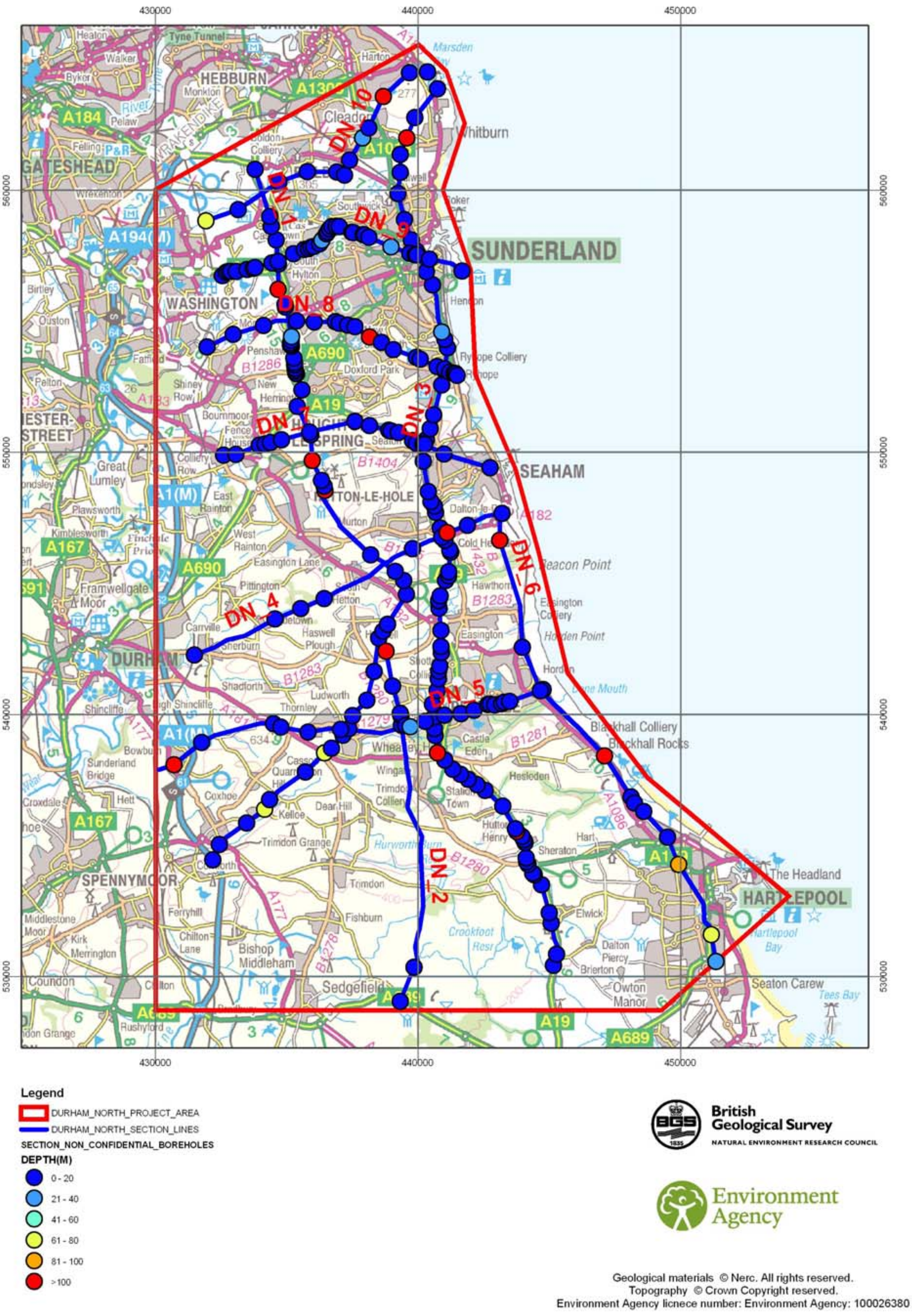


Figure 5 Location of cross-sections and non-confidential boreholes used in interpretation

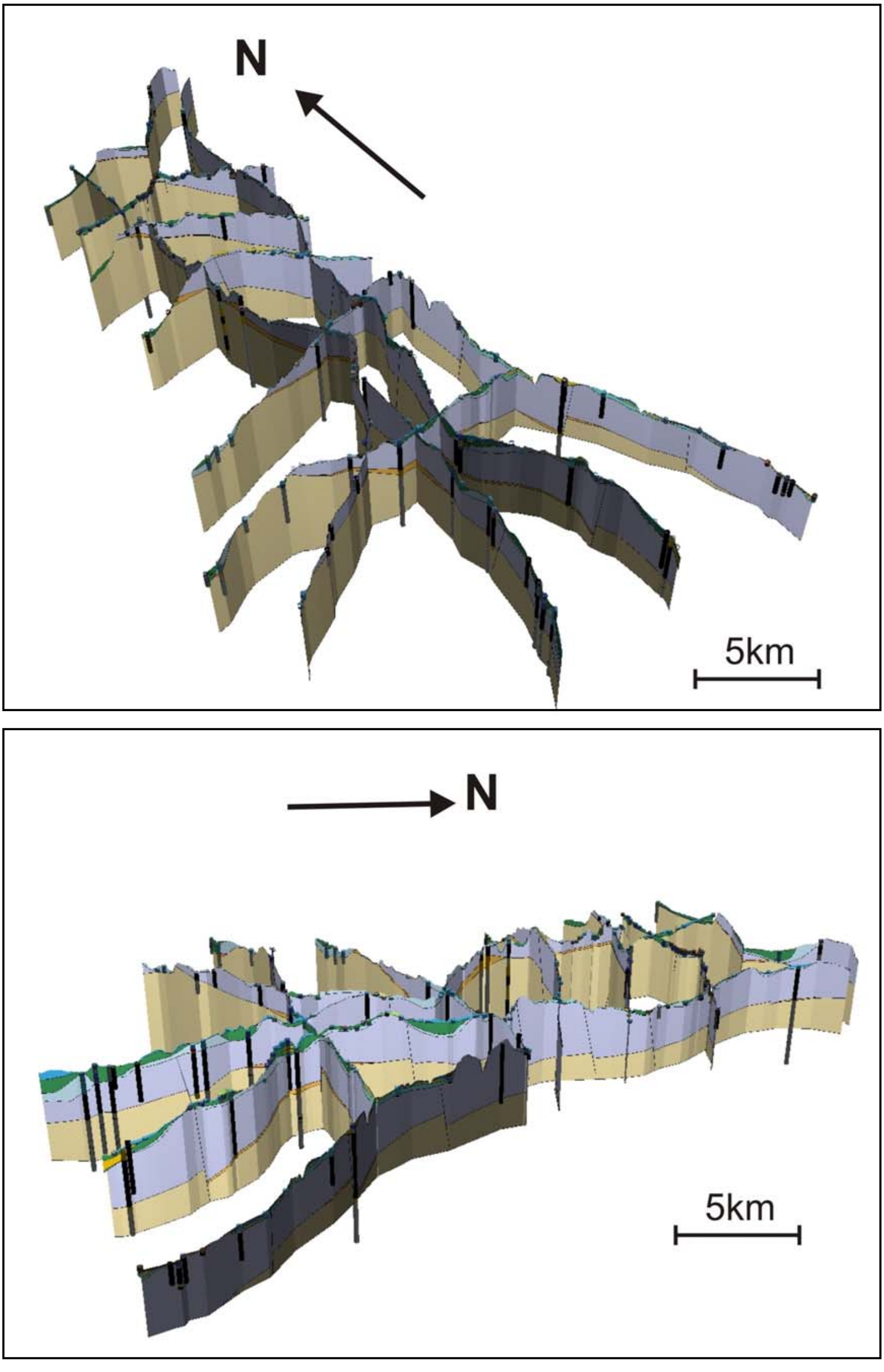


Figure 6 Durham North cross-sections in 3-D

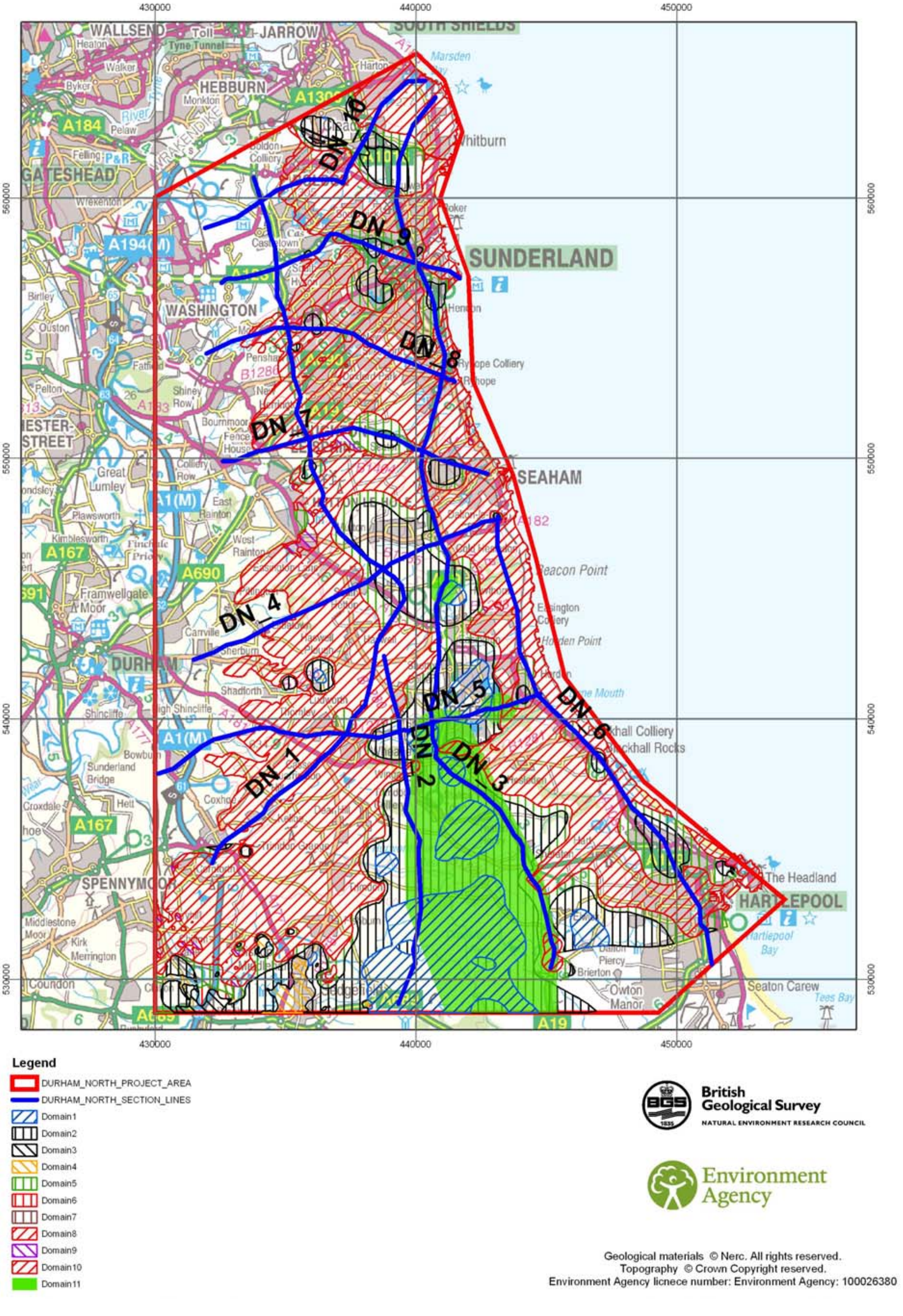


Figure 7 Hydrogeological domains Durham North

Blank areas represent superficial deposits underlain by bedrock other than Permian Limestone or Permian Yellow Sands Formation.

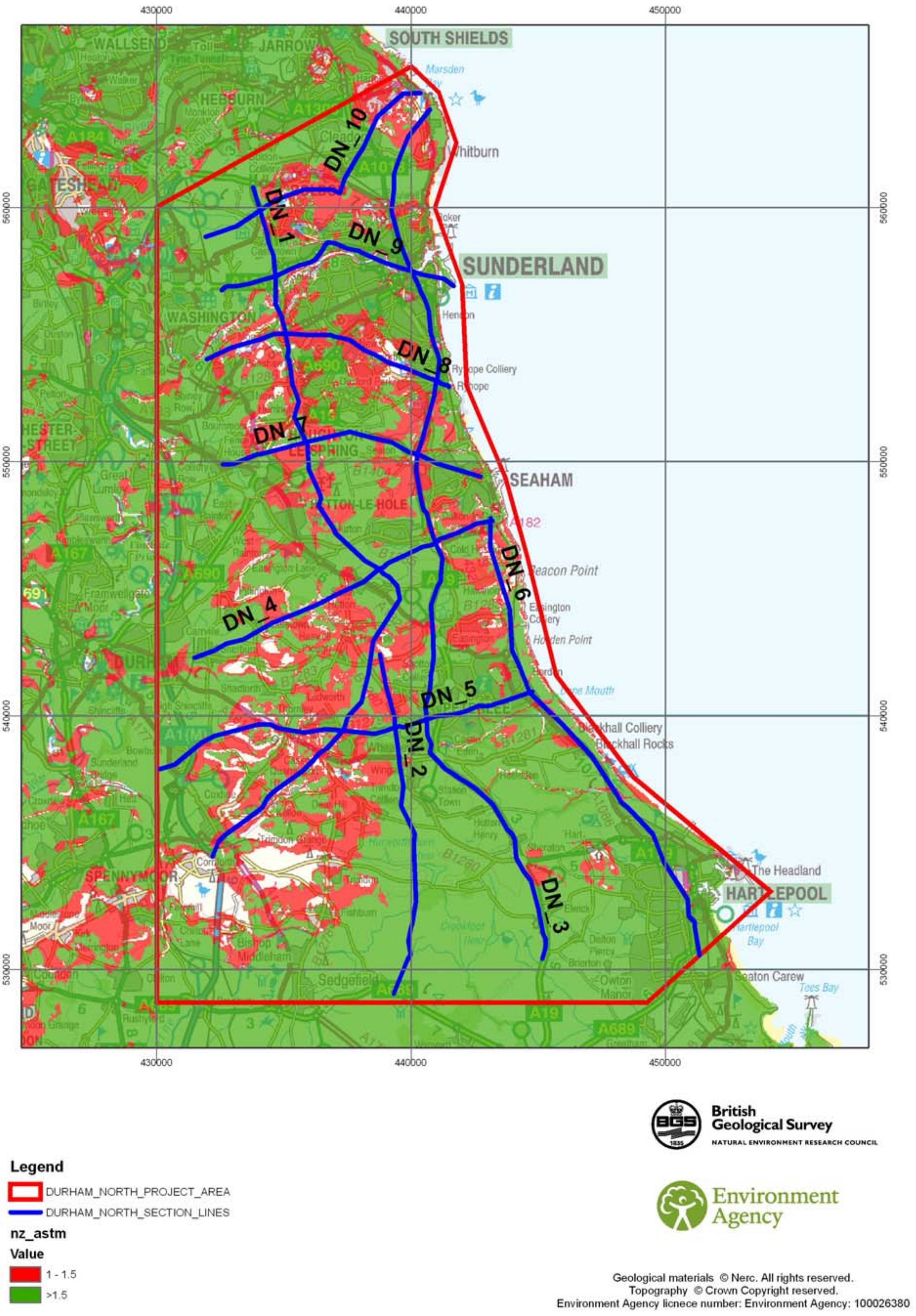


Figure 8 Superficial deposits less than 1.5 m thick. From BGS Superficial Deposits Thickness (ASTM) data. White areas denote bedrock at surface.

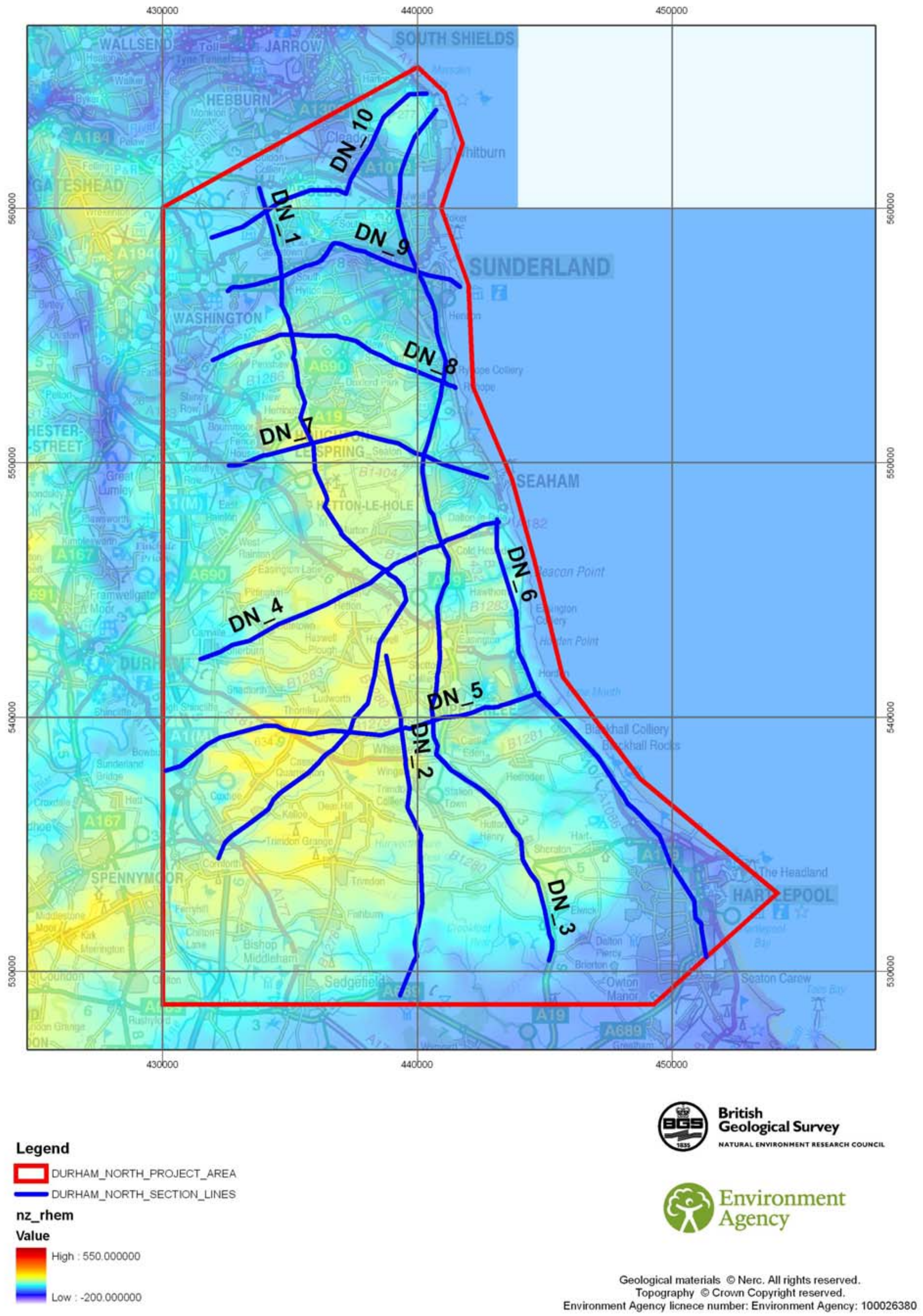


Figure 9 Rockhead elevation (mAOD) from BGS Rockhead Elevation data

Appendix 2 Non-confidential cross-section boreholes

Non-confidential boreholes used in the construction of cross-sections. NA = Not Applicable (used where a synthetic point has been used to constrain the orientation of the section and has no depth).

DN_1

BOREHOLE_NAME	EASTING	NORTHING	DEPTH(M)
Coordinate	432179	534451	N/A
NZ33NW241.	432421	535031	10
Coordinate	433458	535855	N/A
NZ33NW48.	434153	536376	68
Coordinate	434345	536755	N/A
Coordinate	435701	537798	N/A
Bankdam	436430	538540	63
Coordinate	436699	538718	N/A
Coordinate	437133	539205	N/A
Coordinate	437356	539460	N/A
NZ33NE87.	437500	539951	10
NZ34SE52.	438048	540541	10
Coordinate	438323	541642	N/A
NZ34SE59.	438500	542911	7
NZ34SE60.	438655	543174	10
NZ34SE61.	438834	543436	6
Coordinate	439550	544583	N/A
Coordinate	439455	545104	N/A
NZ34NE79.	439134	545458	7
Coordinate	438189	546093	N/A
NZ34NE98.	436452	548554	252
NZ34NE131.	436420	548710	3
NZ34NE130.	436320	548930	2
NZ34NE115.	435970	549690	290
Coordinate	435909	550671	N/A
Coordinate	435400	551759	N/A
NZ35SE162 153	435575	552378	5
NZ35SE162 162	435359	552994	6
NZ35SE162 164	435331	553028	5
NZ35SE162 165	435318	553119	5
NZ35SE162 167	435305	553208	12
NZ35SE162 168	435292	553330	7

NZ35SE162 169	435285	553420	5
NZ35SE162 171	435265	553602	2
NZ35SE162 176	435173	554048	17
NZ35SE169.	435133	554094	11
NZ35SE162 177	435134	554171	17
NZ35SE173.	435153	554280	13
NZ35SE262.	435178	554427	22
NZ35NW472.	434935	555541	10
NZ35NW473.	434931	555653	5
NZ35NW32.	434667	556227	365
NZ35NW77 214	434680	557186	7
NZ35NW77 216	434664	557294	3
NZ35NW557.	434590	558110	8
NZ35NW543.	434395	558623	3
NZ35NW542.	434335	559006	8
NZ36SW76 254	433780	560800	12

DN_2

BOREHOLE_NAME	EASTING	NORTHING	DEPTH(M)
Coordinate	439321	529050	N/A
Coordinate	439848	530358	N/A
Coordinate	439366	539595	N/A
NZ33NE150.	439350	539940	6
NZ34SE112.	439320	540040	6
Coordinate	439027	541088	N/A
Tuthill	438770	542410	136

DN_3

BOREHOLE_NAME	EASTING	NORTHING	DEPTH(M)
Coordinate	445160	530429	N/A
NZ43SE18.	445278	530850	8
NZ43SE26.	445078	532031	5
Coordinate	444992	532425	N/A
Coordinate	444708	533497	N/A
NZ43SW29 W	444425	533875	9
NZ43SW29 T	444374	533945	3
NZ43SW29 Y	444191	534281	6
NZ43SW29 F	444138	534379	12
NZ43SW29 C	444119	534520	5
NZ43NW60.	444079	535105	18

NZ43NW53.	444034	535208	15
Coordinate	443964	535337	N/A
NZ43NW235.	443759	535531	201
NZ43NW50.	443711	535639	4
Coordinate	443221	536503	N/A
NZ43NW66 5	442548	537107	12
NZ43NW66 10	442246	537324	5
NZ43NW66 14	441906	537525	12
NZ43NW66 20	441622	537722	8
NZ43NW66 23	441330	537907	6
NZ43NW66 27	441021	538253	18
New Winning	440740	538530	153
Coordinate	440649	539197	N/A
Coordinate	440616	539462	N/A
Coordinate	440612	539903	N/A
NZ44SW561.	440549	540393	10
NZ44SW481.	440719	540905	7
NZ44SW503.	440772	541361	13
NZ44SW948.	440780	541650	10
NZ44SW523.	440822	541839	14
NZ44SW670.	440886	542363	3
NZ44SW239 B	440873	542596	11
NZ44SW934.	440862	543200	11
NZ44SW215 61	440789	544054	3
NZ44SW215 66	440781	544333	3
NZ44SW215 67	440787	544353	3
Coordinate	440840	544516	N/A
Coordinate	441040	545104	N/A
NZ44NW43 80	441165	545281	9
Coordinate	441163	545452	N/A
NZ44NW43 92	441236	546199	6
NZ44NW43 93	441210	546285	6
NZ44NW227.	441023	546644	11
Coordinate	440845	547112	N/A
NZ44NW40 G	440668	547711	16
NZ44NW40 J	440616	547953	8
NZ44NW40 L	440483	548124	9
Coordinate	440389	548500	N/A
Coordinate	440192	549669	N/A
NZ45SW246.	440240	550310	5
NZ45SW259.	440310	550500	5

NZ45SW192 E	440453	550899	3
Coordinate	440592	551433	N/A
Coordinate	440905	552579	N/A
Coordinate	440983	553151	N/A
NZ45SW13238 9	441020	553190	4
NZ45SW212.	441112	554002	4
Coordinate	441019	554312	N/A
NZ45SW46.	440900	554600	38
Coordinate	440541	556391	N/A
NZ45NW113.	440310	556890	18
NZ35NE213 L	439994	557561	28
NZ35NE104 B	439930	557690	6
Coordinate	439747	558115	N/A
NZ35NE519.	439480	558880	6
Coordinate	439230	559880	N/A
NZ36SE36.	439320	560680	6
Coordinate	439324	561367	N/A
NZ36SE59.	439560	562010	336
Coordinate	439873	562787	N/A
Coordinate	440741	563878	N/A

DN_4

BOREHOLE_NAME	EASTING	NORTHING	DEPTH(M)
Coordinate	431468	542273	N/A
Coordinate	434541	543645	N/A
Coordinate	435521	544042	N/A
Coordinate	436420	544426	N/A
Coordinate	439784	546319	N/A
NZ44NW231.	440899	546767	6
Dalton	441110	546940	165
Coordinate	441873	547220	N/A
Coordinate	443196	547664	N/A

DN_5

BOREHOLE_NAME	EASTING	NORTHING	DEPTH(M)
NZ33NW50.	430700	538076	138
Coordinate	431754	538931	N/A
NZ33NW186.	434483	539643	2
NZ33NW190.	434758	539509	2
Coordinate	435801	539329	N/A

NZ33NE85.	437045	539430	7
NZ33NE94.	439526	539580	14
NZ33NE99.	439693	539535	24
Coordinate	440267	539740	N/A
Coordinate	440996	539976	N/A
NZ44SW309.	441637	540032	6
NZ44SW93.	442130	540165	3
Coordinate	442658	540383	N/A
NZ44SW272.	442738	540391	6
Coordinate	442921	540367	N/A
NZ44SW131.	443178	540404	5
NZ44SW130.	443284	540461	5
NZ44SW86.	443491	540500	3
Coordinate	444765	540952	N/A

DN_6

BOREHOLE_NAME	EASTING	NORTHING	DEPTH(M)
Kinley Hill	443110	546640	188
Coordinate	443967	542563	N/A
Coordinate	444666	540901	N/A
NZ43NE3.	447106	538413	105
Coordinate	448116	536857	N/A
Coordinate	448250	536613	N/A
NZ43NE85.	448600	536300	13
NZ43NE13541 6	449510	535320	11
NZ43SE74.	449930	534270	99
NZ53SW130.	451170	531600	61
NZ53SW60.	451346	530565	25

DN_7

BOREHOLE_NAME	EASTING	NORTHING	DEPTH(M)
Coordinate	432587	549894	N/A
NZ34NW114 A	433044	549924	6
NZ35SW307.	433940	550280	7
Coordinate	434159	550314	N/A
NZ35SW57 24	434374	550376	2
Coordinate	434788	550487	N/A
Coordinate	435860	550774	N/A
Coordinate	437589	551179	0
NZ35SE163.	438149	551030	13

NZ35SE162 108	438882	550841	12
NZ35SE162 107	438971	550823	6
NZ35SE162 105	439238	550767	6
NZ35SE162 96	439786	550455	14
NZ35SE185.	439936	550354	10
NZ45SW245.	440180	550320	7
NZ45SW246.	440240	550310	5
Coordinate	440992	549937	N/A
Coordinate	442737	549411	N/A

DN_8

BOREHOLE_NAME	EASTING	NORTHING	DEPTH(M)
Coordinate	431956	554029	N/A
Coordinate	432952	554509	N/A
NZ35SW25.	434102	554840	13
NZ35NE157 F	435367	555025	10
NZ35SE15 B	436041	554979	17
NZ35SE19 C	436848	554990	5
NZ35SE19 F	436987	554931	2
NZ35SE20 F	437309	554862	7
NZ35SE20 H	437589	554794	2
NZ35SE14.	438152	554401	101
NZ35SE188 E	438606	554202	3
Coordinate	439052	553926	N/A
NZ35SE188 A	439939	553624	2
NZ45SW13238 14	440080	553550	5
NZ45SW13238 10	440730	553280	2
NZ45SW13238 9	441020	553190	4
NZ45SW13238 4	441200	553060	5
NZ45SW13238 2	441360	553020	5
NZ45SW13238 1	441430	553010	7
Coordinate	441487	552938	N/A

DN_9

BOREHOLE_NAME	EASTING	NORTHING	DEPTH(M)
NZ35NW107.	432545	556751	6
NZ35NW98 A	432686	556879	6
NZ35NW98 C	432767	556906	5
NZ35NW98 D	432864	556903	5
NZ35NW123.	433071	556906	17

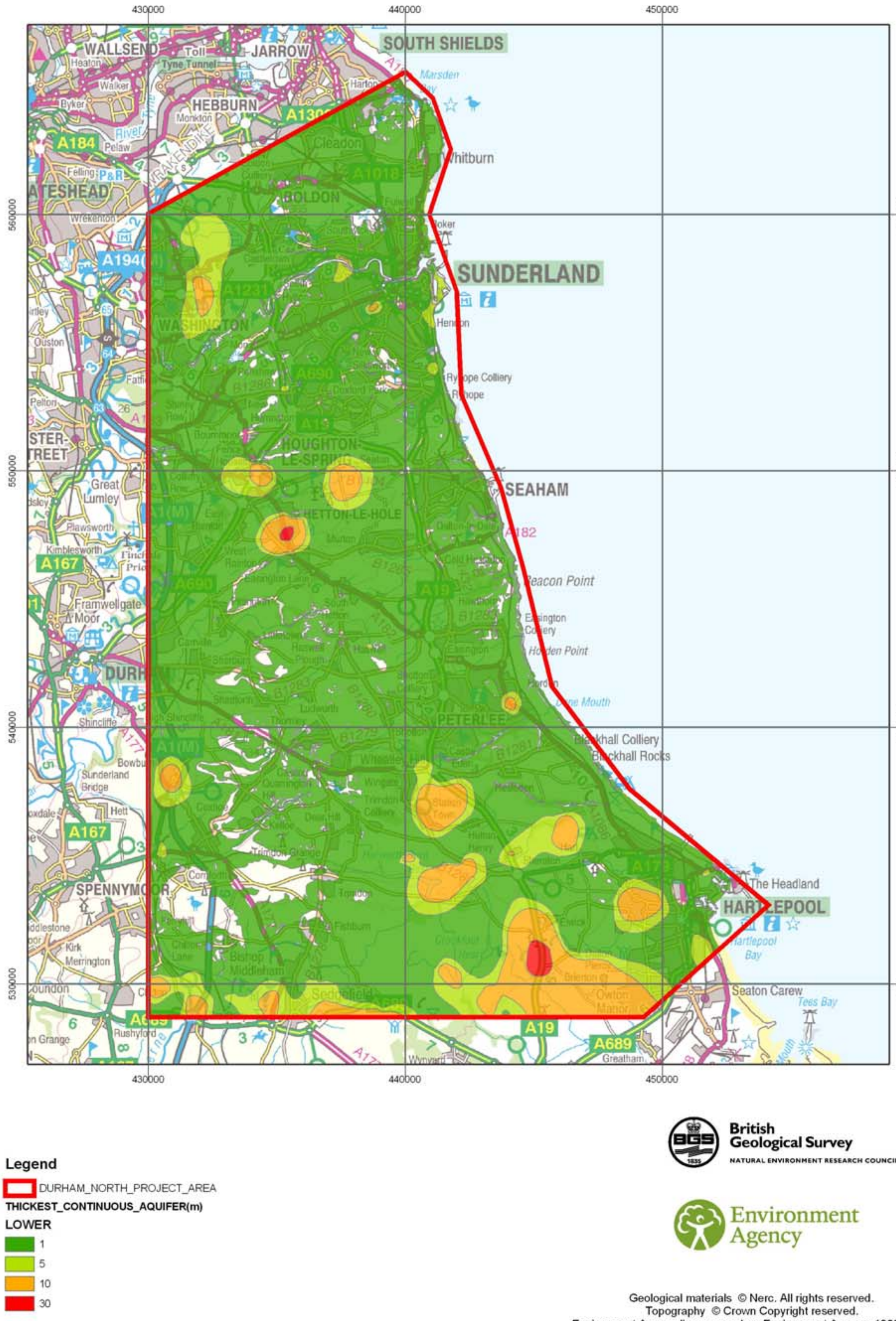
NZ35NW121.	433479	556984	14
NZ35NW98 N	433706	557031	8
NZ35NW98 P	433785	557053	3
NZ35NW98 W	434421	557234	7
NZ35NW77 216	434664	557294	3
NZ35NE224 V	435250	557580	18
NZ35NE224 J	435650	557750	11
NZ35NE224 G	435820	557780	13
NZ35NE224 F	435920	557830	13
NZ35NE224 E	436030	557860	13
NZ35NE338.	436239	557966	12
NZ35NE344.	436329	558089	23
NZ35NE535.	436500	558340	7
NZ35NE494.	436550	558420	15
NZ35NE9.	436630	558530	8
Coordinate	436711	558627	N/A
NZ35NE775.	436870	558630	17
NZ35NE195 A	436990	558620	9
NZ35NE13447 4	437470	558400	11
NZ35NE420.	437531	558381	5
NZ35NE47.	437910	558310	11
NZ35NE56.	437960	558300	11
NZ35NE59 C	438120	558210	6
NZ35NE87 1	438960	557840	23
NZ35NE215 A	439690	557600	3
NZ35NE213 K	439890	557534	24
NZ35NE208.	439940	557540	18
Coordinate	440425	557375	N/A
Coordinate	441675	556918	N/A

DN_10

BOREHOLE_NAME	EASTING	NORTHING	DEPTH(M)
NZ35NW15.	431903	558847	71
Coordinate	433137	559271	N/A
Coordinate	434685	560317	N/A
Coordinate	435777	560714	N/A
Coordinate	436896	560708	N/A
Coordinate	437194	560582	N/A
Coordinate	437386	561151	N/A
NZ36SE26.	437880	562010	33
Coordinate	438120	562382	N/A

NZ36SE106.	438670	563590	116
Coordinate	439676	564487	N/A
Coordinate	440357	564520	N/A

Appendix 3 Aquitard and Aquifer thickness maps



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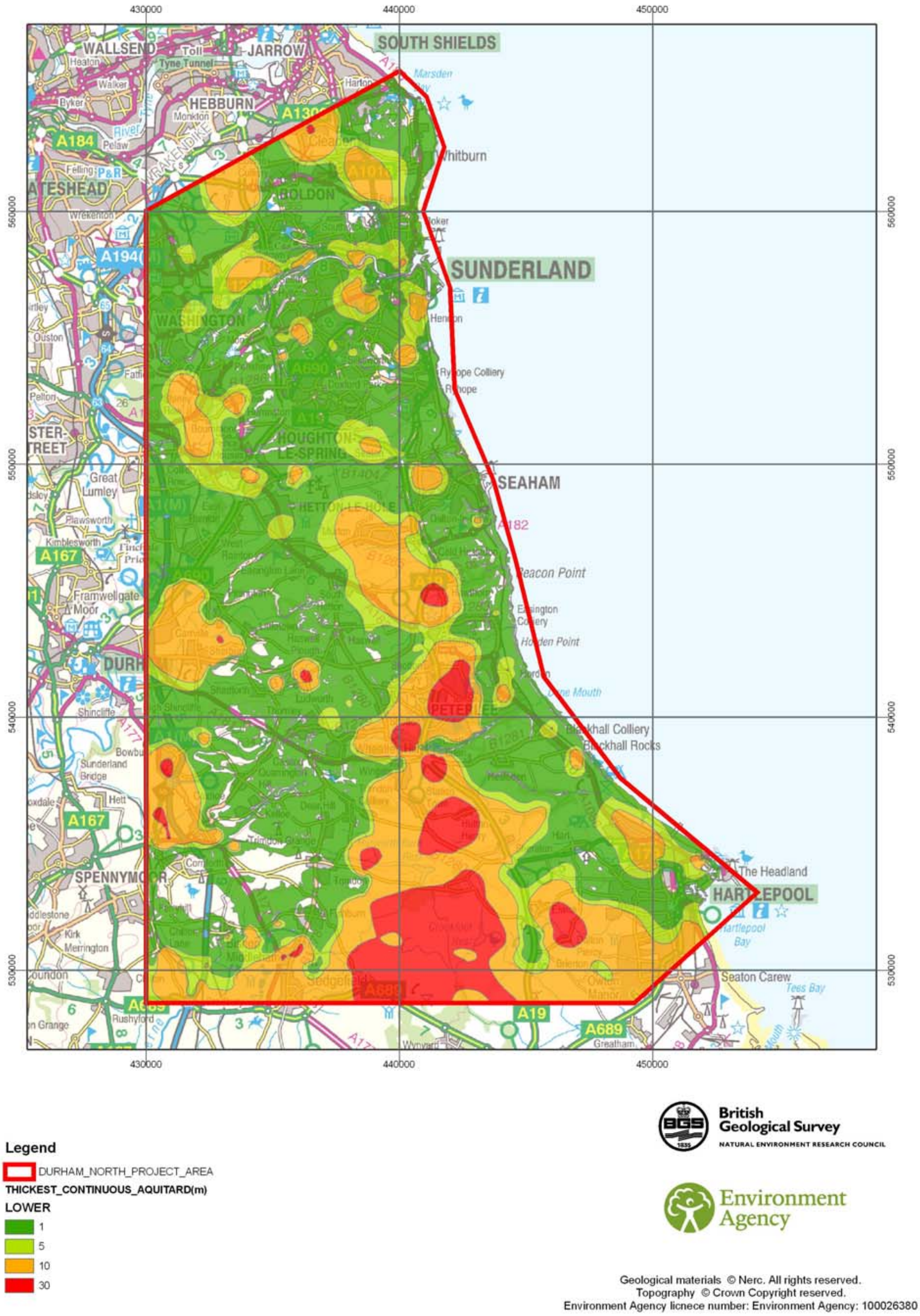
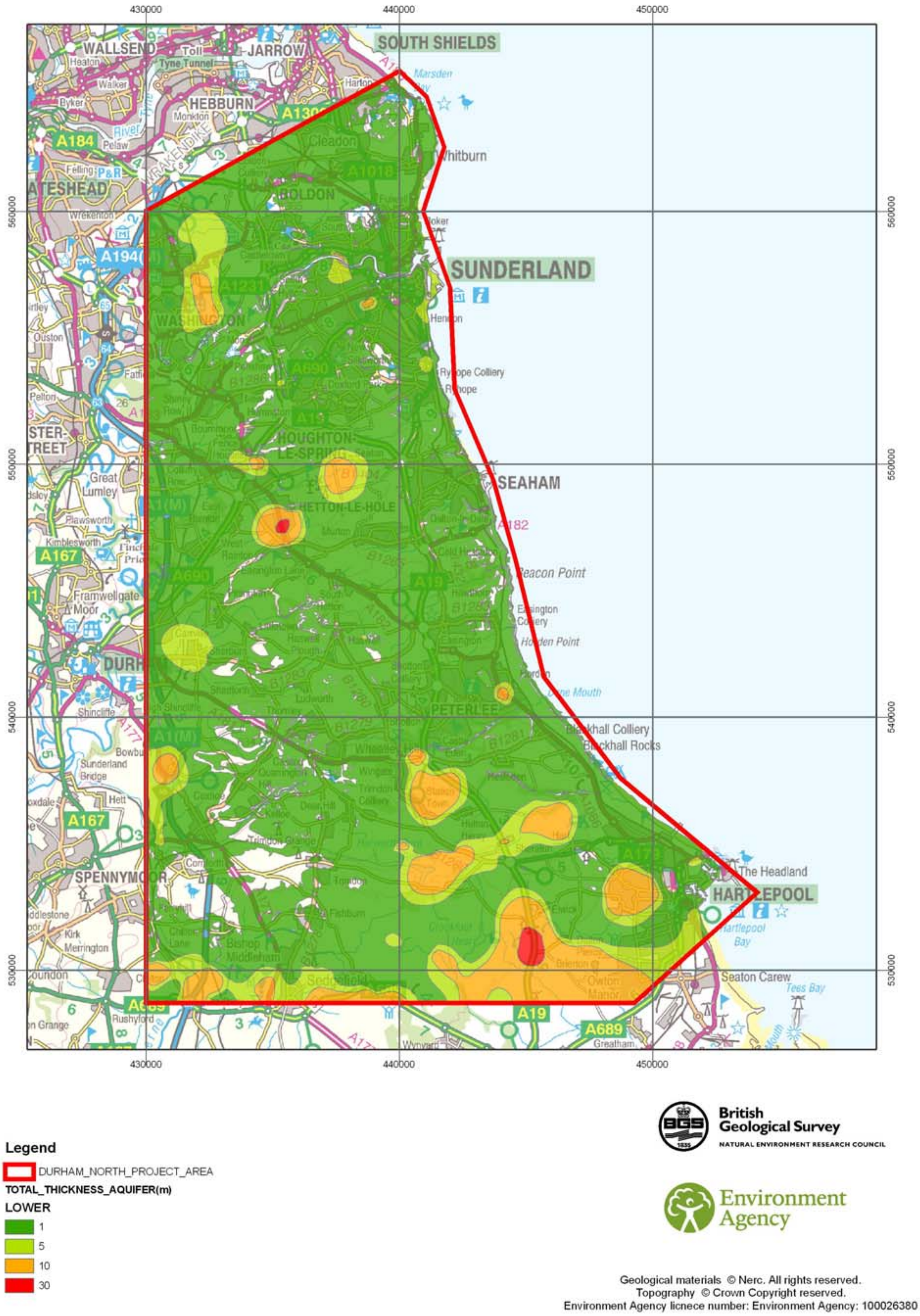
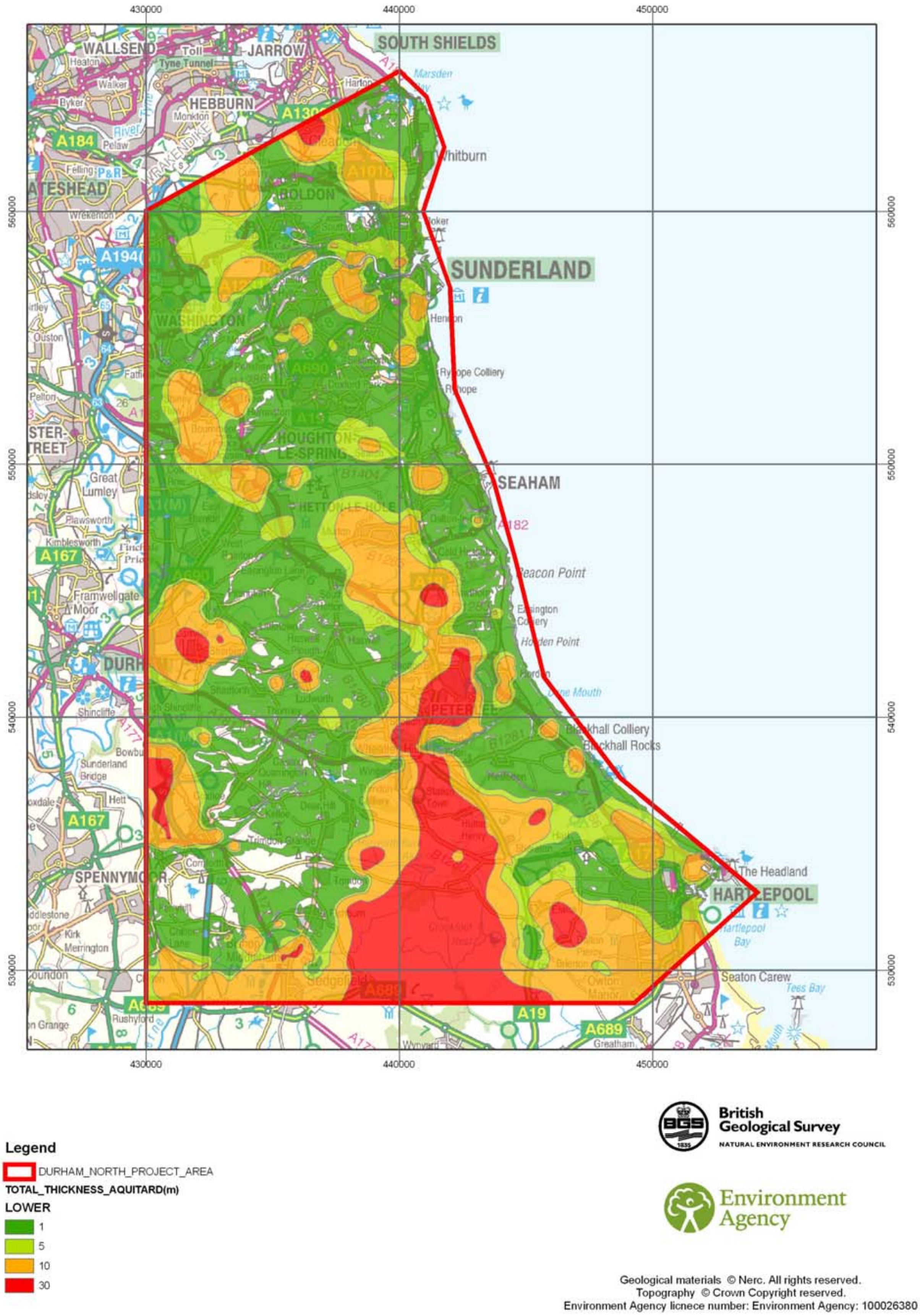
Thickest continuous aquifer (superficial deposits). All thicknesses metres (m).



Thickest continuous aquitard (superficial deposits). All thicknesses metres (m).



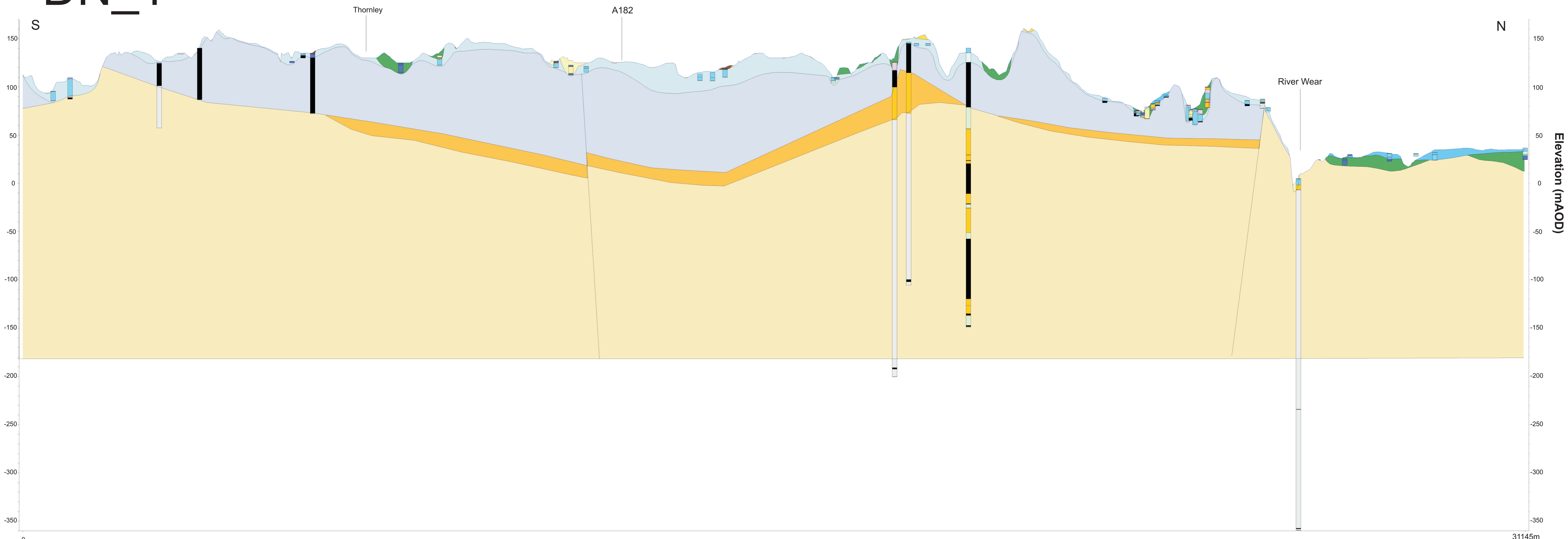
Total thickness of aquifer (superficial deposits). All thicknesses metres (m).



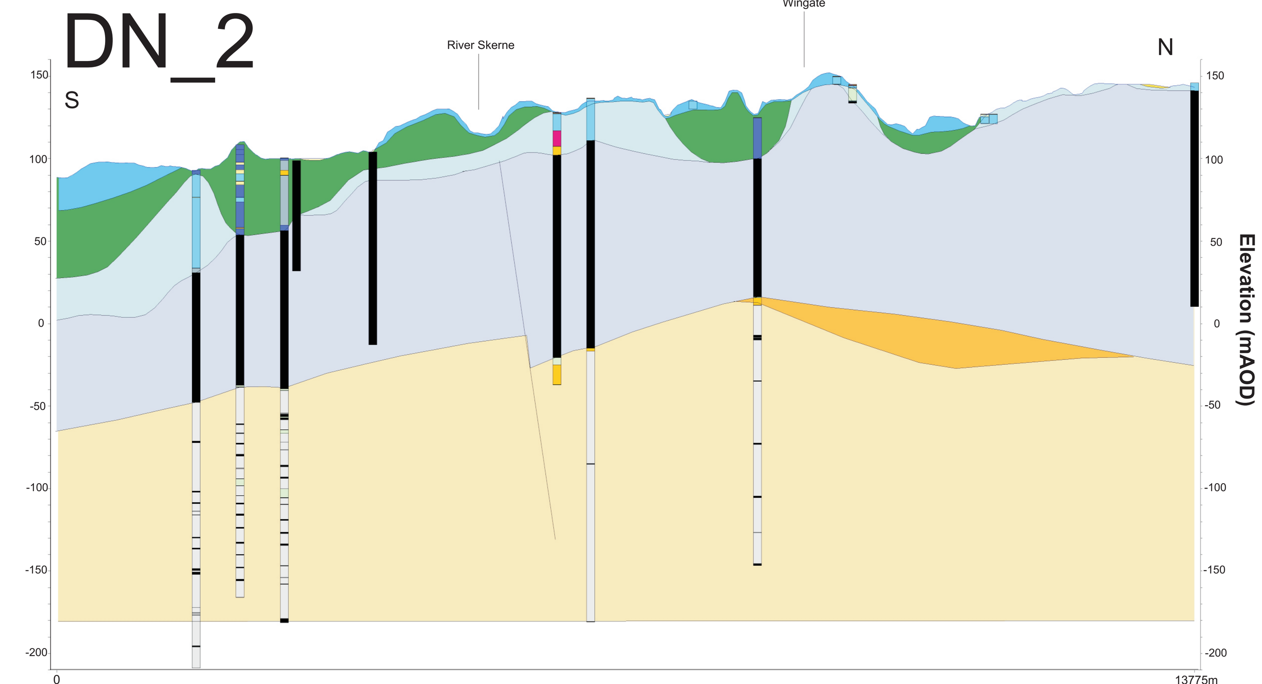
Total thickness of aquitard (superficial deposits). All thicknesses metres (m).

Appendix 4 Cross-Sections

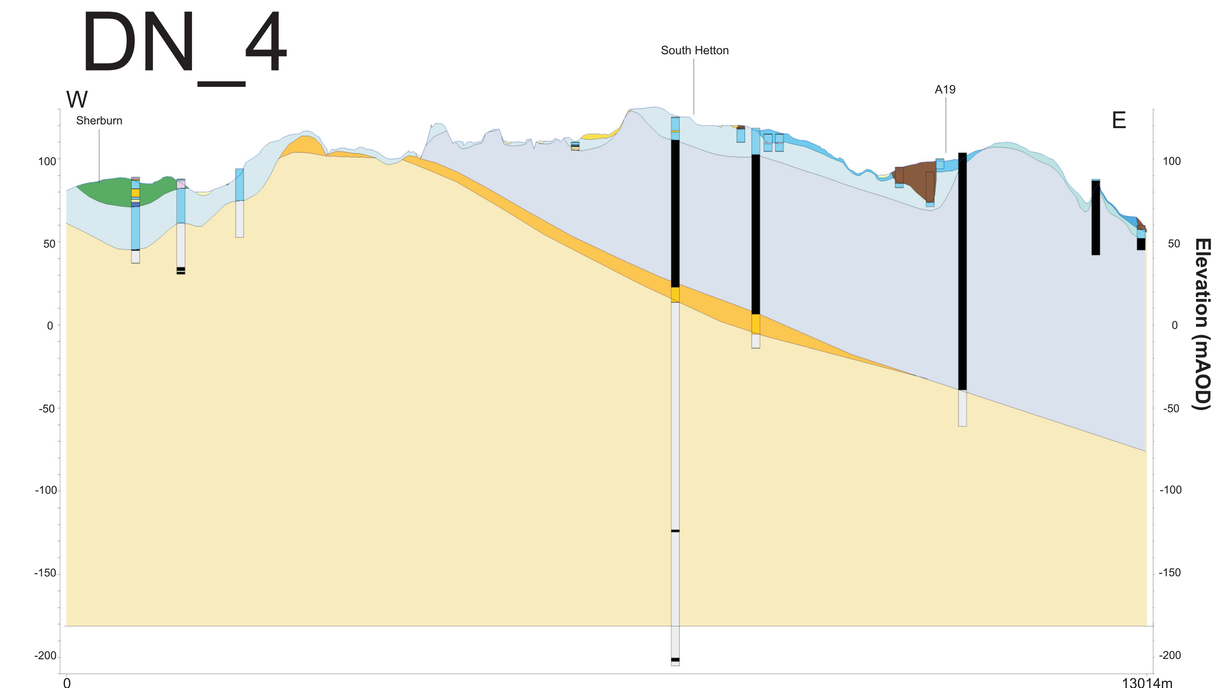
DN_1



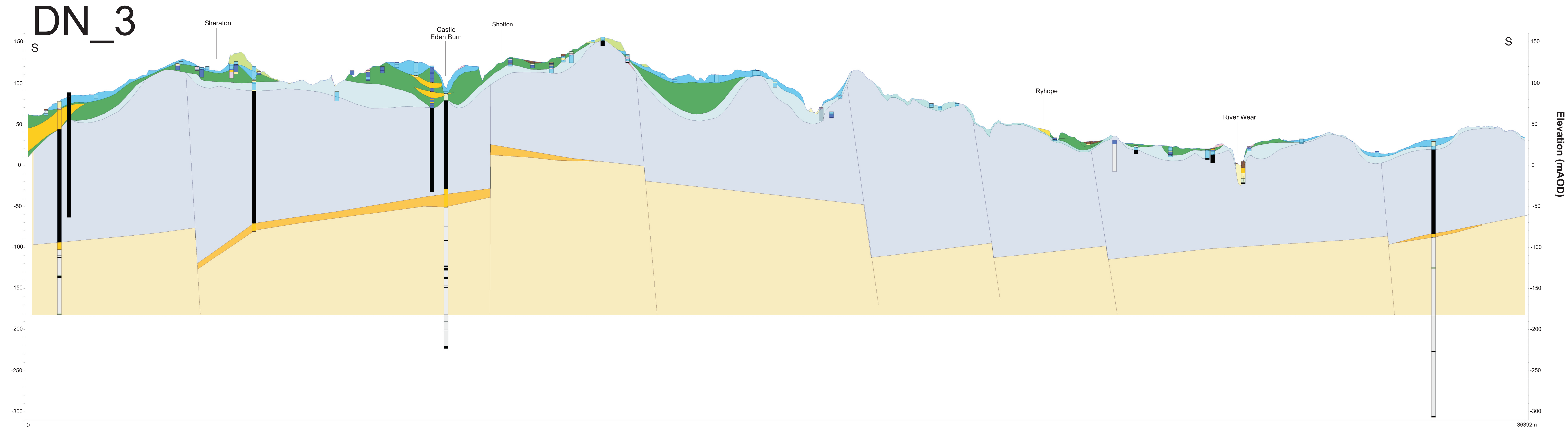
DN_2



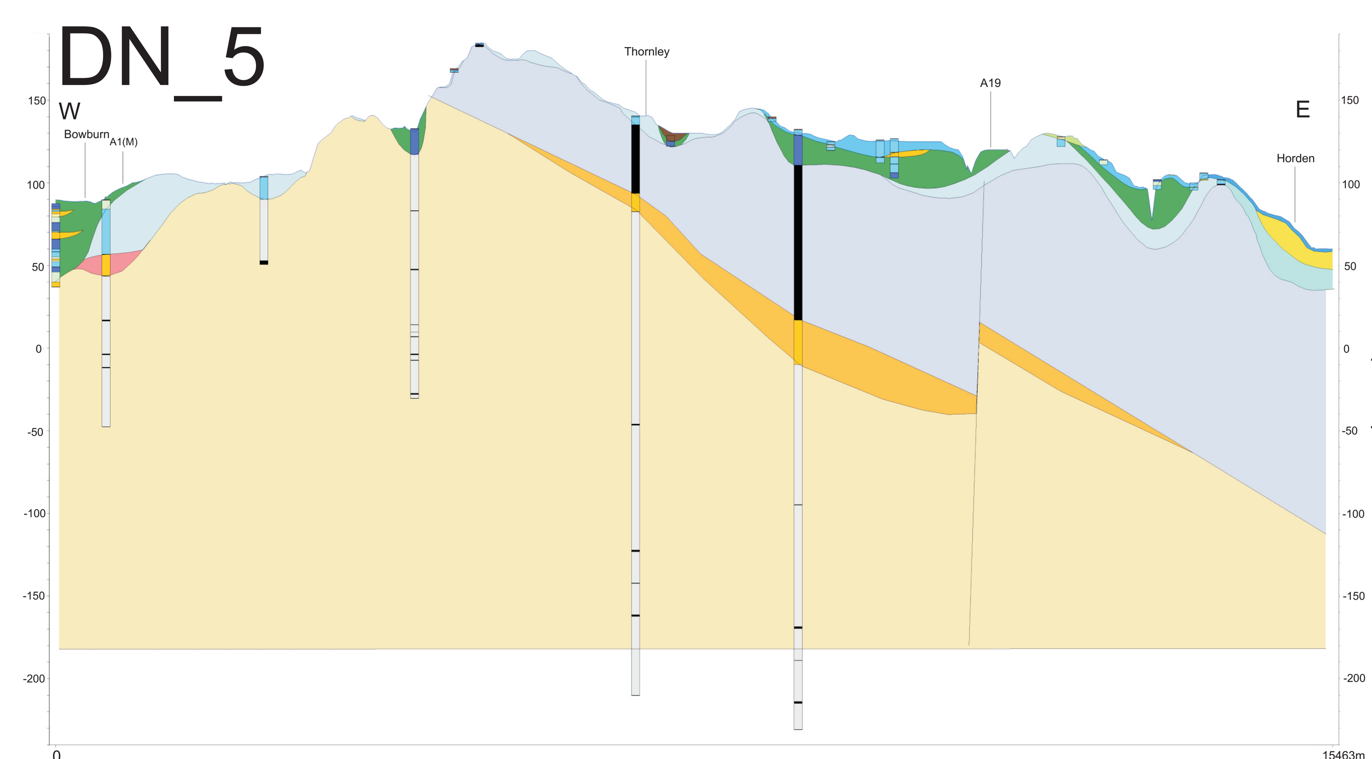
DN_4



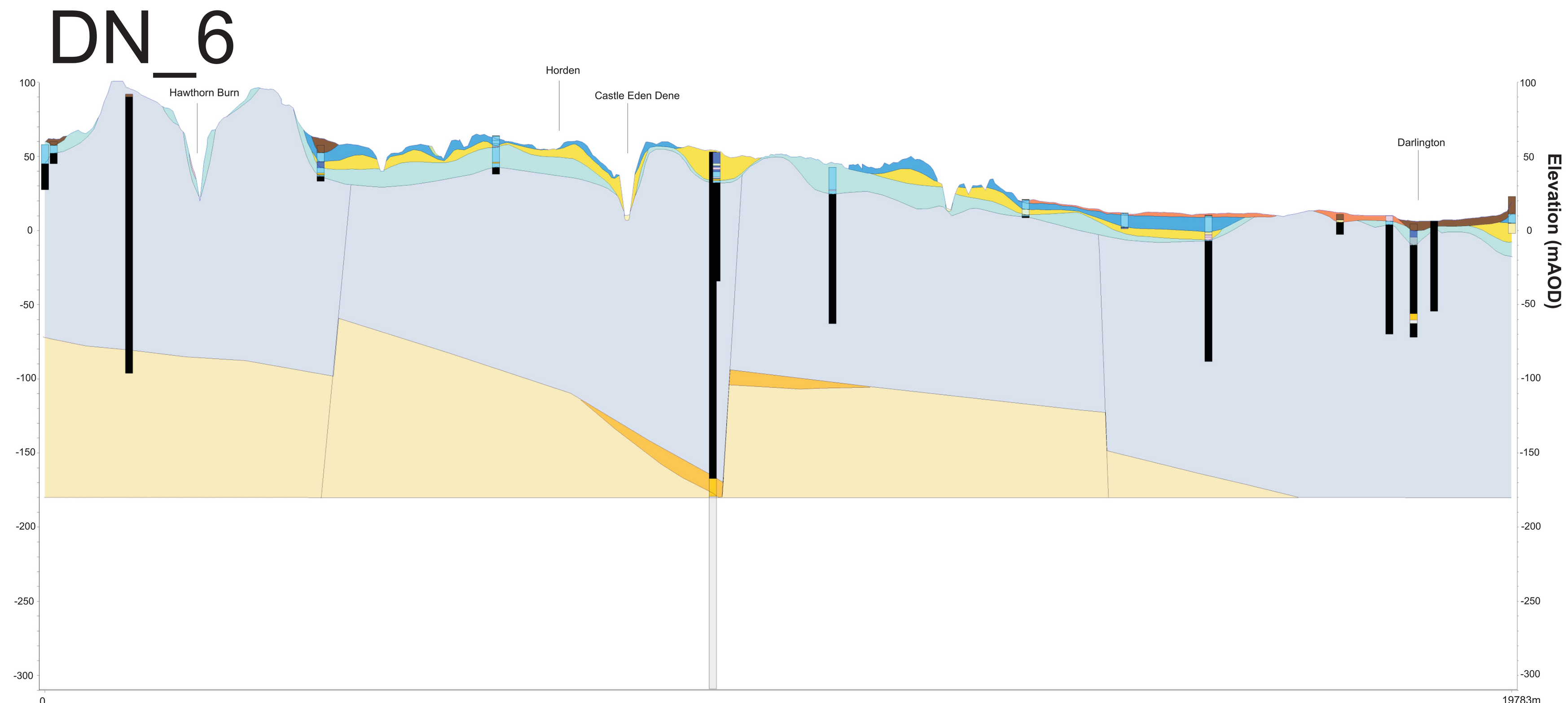
DN_3



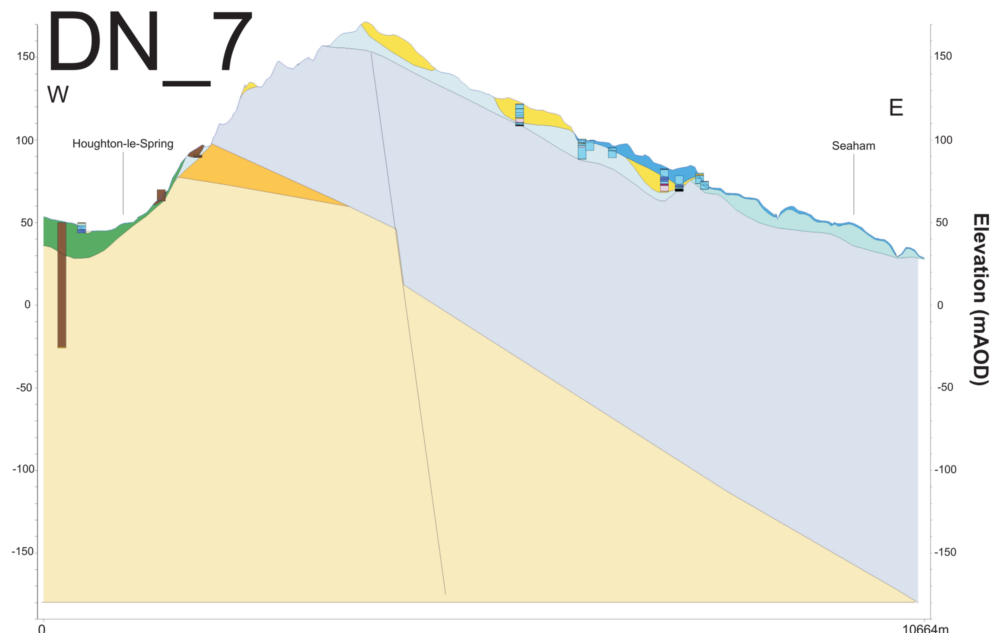
DN_5



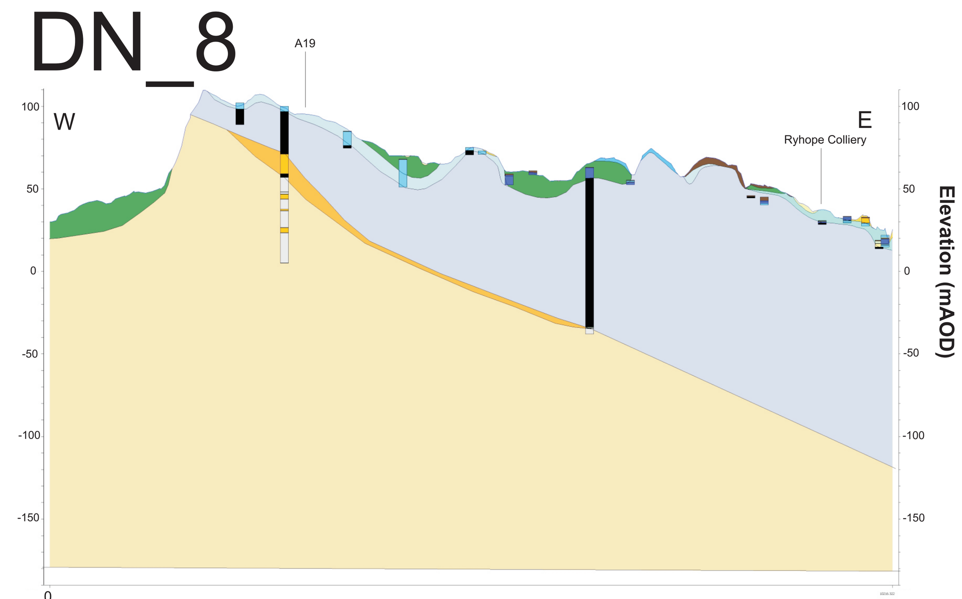
DN_6



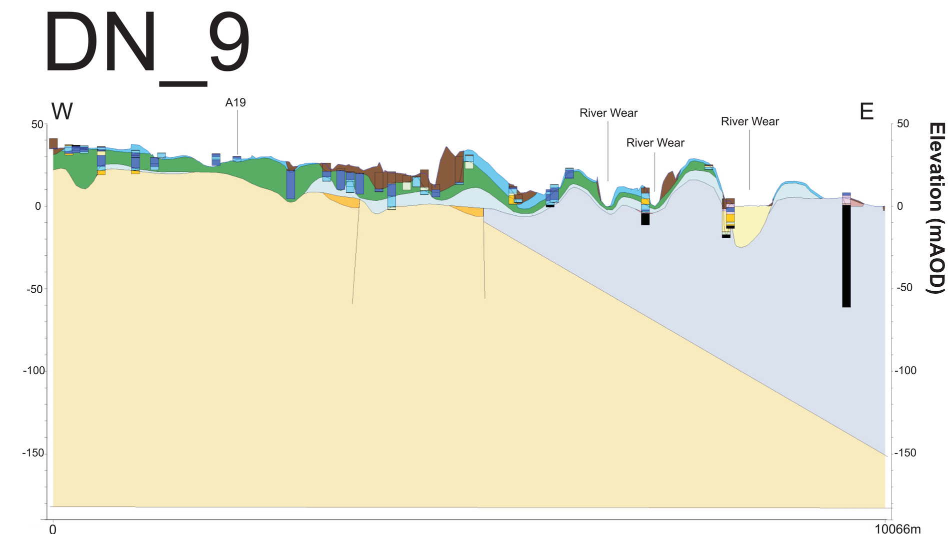
DN_7



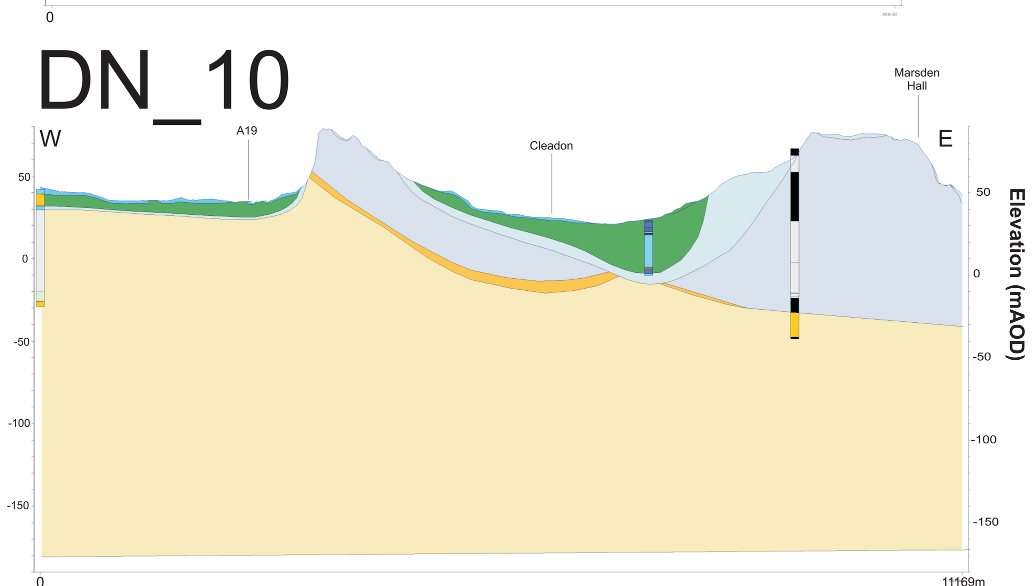
DN_8



DN_9



DN_10



Superficial Deposits

- Made Ground (18)
- Marine (17)
- River Terrace Deposits (16)
- Alluvium (15)
- Peat (14)
- Lacustrine (13)
- Tidal Flat Deposits (12)
- Raised Marine Deposits (11)

North Pennine Glacigenic Subgroup

- Ebchester Sand and Gravel Formation (10)
- Moraine (9)
- Butterby Till Formation (6)
- Tyne and Wear Glaciolacustrine Formation(4) *including lenses of sand or sand and gravel*
- Wear Till Formation (2)
- Maiden's Hall sand and Gravel Formation (1)

North Sea Coast Glacigenic Subgroup

- Elwick Moraine Member (8)
- Horden Till Formation (7)
- Peterlee Sand Formation (5)
- Blackhall Till Formation (3)

Lithology of Superficial Deposits in Borehole Logs

- Soil or Made Ground
- Gravelly Clay
- Clay or Silt and Clay
- Silt and sandy Silt
- Sand
- Sand and Gravel
- Boulder
- Superficial Deposits Undifferentiated

Bedrock

- Permian Limestone
- Permian Yellow Sands
- Carboniferous Coal Measures and Namurian Stainmore Formation

Bedrock correlations are shown schematically only

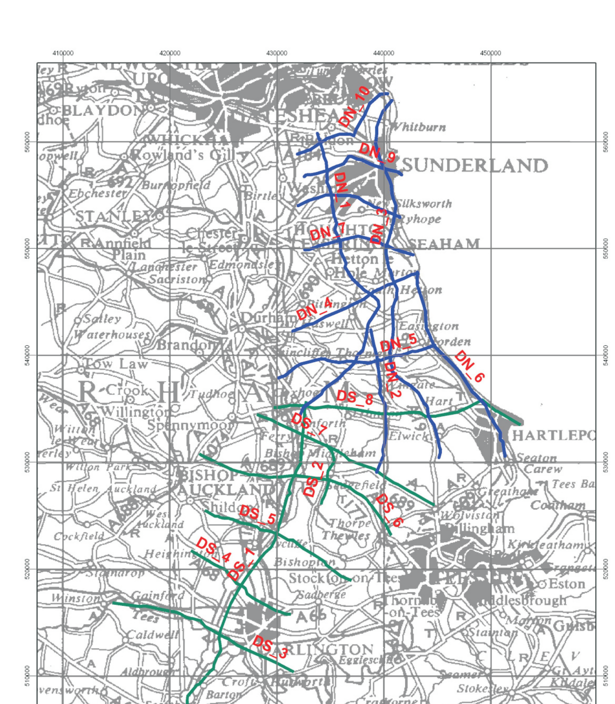
Horizontal Scale 1:50 000
Vertical Exaggeration x 20

Durham North Magnesian Limestone Study Phase 2
In confidence report CR/07/022

KEY

Durham North Superficial Geology section lines (Phase 2)

Durham South Superficial Geology section lines (Phase 1)



The cross-sections are compiled from borehole information that varies considerably in distribution, age, quality, depth and content. The geological information has been compiled from these boreholes and digital map data at a scale of 1: 50 000. Use of the cross-section interpretations at scales larger than 1:50 000 is not recommended. The varied distribution of the borehole data means that in some places the sections are well constrained and in others the geological lines are considerably extrapolated. The cross-sections are the best interpretation that the geologist has been able to make from the existing information and new boreholes may require this interpretation to be modified.

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